
ACRIM total solar irradiance satellite composite validation versus TSI proxy models

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Abstract The satellite total solar irradiance (TSI) database provides a valuable record for investigating models of solar variation used to interpret climate changes. The 35-year ACRIM total solar irradiance (TSI) satellite composite time series has been updated using corrections to ACRIMSAT/ACRIM3 results for scattering and diffraction derived from recent testing at the Laboratory for Atmospheric and Space Physics/Total solar irradiance Radiometer Facility (LASP/TRF). The corrections lower the ACRIM3 scale by about 5000 ppm, in close agreement with the scale of SORCE/TIM results (solar constant $\approx 1361 \text{ W/m}^2$) but the relative variations and trends are not changed. Differences between the ACRIM and PMOD TSI composites, particularly the decadal trending during solar cycles 21-22, are tested against a set of solar proxy models, including analysis of Nimbus7/ERB and ERBS/ERBE results available to bridge the ACRIM Gap (1989-1992). Our findings confirm the following ACRIM TSI composite features: (1) The validity of the TSI peak in the originally published ERB results in early 1979 during solar cycle 21; (2) The correctness of originally published ACRIM1 results during the SMM spin mode (1981-1984); (3) The upward trend of originally published ERB results during the ACRIM Gap; (4) The occurrence of a significant upward TSI trend between the minima of solar cycles 21 and 22 and (5) a decreasing trend during solar cycles 22 - 23. Our findings do not support the following PMOD TSI composite features: (1) The downward corrections to originally published ERB and ACRIM1 results during solar cycle 21; (2) A step function sensitivity change in ERB results at the end-of-September 1989; (3) the validity of ERBE's downward trend during the ACRIM Gap or (4) the use of ERBE results to bridge the ACRIM Gap. Our analysis provides a first order validation of the ACRIM TSI composite approach and its 0.037%/decade upward trend during solar cycles 21-22. The implications of increasing TSI during the global warming of the last two decades of the 20th century are that solar forcing of climate change may be a significantly larger factor than represented in the CMIP5 general circulation climate models.

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1 Introduction

The satellite total solar irradiance (TSI) database is now more than three and a half decades long and provides a valuable record for investigating the relative significance of natural and anthropogenic forcing of climate change (IPCC 2007; Scafetta 2009, 2011). It is made of 7 major independent measurements covering different periods since 1978 (see Figure 1).

A composite TSI record can be constructed from the series of experiments since 1978 by combining and cross-calibrating the set of overlapping satellite observations to create a TSI time series. TSI satellite composites provide end-to-end traceability at the mutual precision level of the overlapping satellite experiments that is orders of magnitude smaller than the absolute uncertainty of the individual experiments. The scale offsets of the various satellite results shown in Figure 1 are caused by the uncertainties of their self-calibration (Willson and Mordvinov 2003; Fröhlich 2012). Different approaches in selecting results and cross-calibrating the satellite records on a common scale have resulted in composites with different characteristics.

Figure 2 shows the two TSI satellite composites most commonly cited: ACRIM (Willson 1997, 2001; Willson and Mordvinov 2003) and PMOD (Fröhlich and Lean 1998; Fröhlich 2004, 2006, 2012). Alternative TSI satellite composites have been proposed by Dewitte et al. (2004) and Scafetta (2011) using different methodologies to merge the datasets.

The new ACRIM composite uses the updated ACRIM3 record. ACRIM3 data was reprocessed after implementing corrections for scattering and diffraction found during recent testing and some other algorithm updates. The testing was performed at the TSI Radiation Facility (TRF) of the Laboratory for Atmospheric and Space Physics (LASP) (Kopp et al. 2007, <http://lasp.colorado.edu/home/>). Two additional algorithm updates were implemented that more accurately account for instrument thermal behavior and parsing of shutter cycle data. These removed a component of the quasi-annual signal from the data and increased the signal to noise ratio of the data, respectively. The net effect of these corrections decreased the average ACRIM3 TSI value from $\sim 1366 \text{ W/m}^2$ (see: Willson and Mordvinov 2003) to $\sim 1361 \text{ W/m}^2$ without affecting the trending in the ACRIM Composite TSI.

Differences between ACRIM and PMOD TSI composites are evident, but the most obvious and significant one is the solar minimum-to-minimum trends during solar cycles 21 to 23. ACRIM presents a bi-decadal increase of $+0.037\%/decade$ from 1980 to 2000 and a

decrease thereafter. PMOD presents a steady multi-decadal decrease since 1978 (see Figure 2). Other significant differences can be seen during the peak of solar cycles 21 and 22. These arise from the fact that ACRIM uses the original TSI results published by the satellite experiment teams while PMOD significantly modifies some results to conform them to specific TSI proxy models (Fröhlich and Lean 1998; Fröhlich 2004, 2006, 2012).

The single greatest challenge in constructing a precise composite extending before 1991 is providing continuity across the two-year ACRIM Gap (1989.53–1991.76) between the results of SMM/ACRIM1 (Willson and Hudson 1991) and UARS/ACRIM2 (Willson 1994, 1997). During this period the only observations available were those of the Nimbus7/ERB (hereafter referred to as ERB) (Hoyt et al. 1992) and ERBS/ERBE (hereafter referred to as ERBE) (Lee III et al. 1995). These experiments provided TSI observations that met the needs of the Earth Radiation Budget investigations at that time, but were less precise and accurate than the ACRIM experiments that were designed specifically to provide the long term precision and traceability required by climate and solar physics investigations.

ACRIM1 and ACRIM2 were intended to overlap initiating an ACRIM TSI monitoring strategy designed to provide long term TSI traceability of results through the precision of on-orbit comparisons. ACRIM2 was delayed by the Challenger disaster, however, and eventually deployed two years after the last data from ACRIM1. This period is known as the ACRIM GAP (1989.5 - 1991.75), as shown in Figure 1.

ACRIM1, ACRIM2 and ACRIM3 were dedicated TSI monitoring experiments capable of highly precise observations by virtue of their design and operation, which includes continuous electronic self-calibration, high duty cycle solar observations (ACRIM1: 55 min./orbit; ACRIM2: 35 min./orbit; ACRIM3: up to full sun during its 96 minute sun-synchronous orbit), sensor degradation self-calibration, high observational cadence (2 minutes) and precise solar pointing. ERB and ERBE were less accurate and precise experiments designed to meet the less stringent data requirements of Earth Radiation Budget modeling. They were able to self-calibrate only infrequently (every 14 days), had limited solar observational opportunities (ERB: 5 min/orbit daily; ERBE: 5 minutes every 14 days, usually) and were not independently solar pointed, observing while the sun moved through their fields of view, all of which degraded their precision and accuracy.

Bridging the ACRIM Gap using ERB and ERBE results is problematical not only because of their lower data quality but also because their results yield significantly different and incompatible trends during the

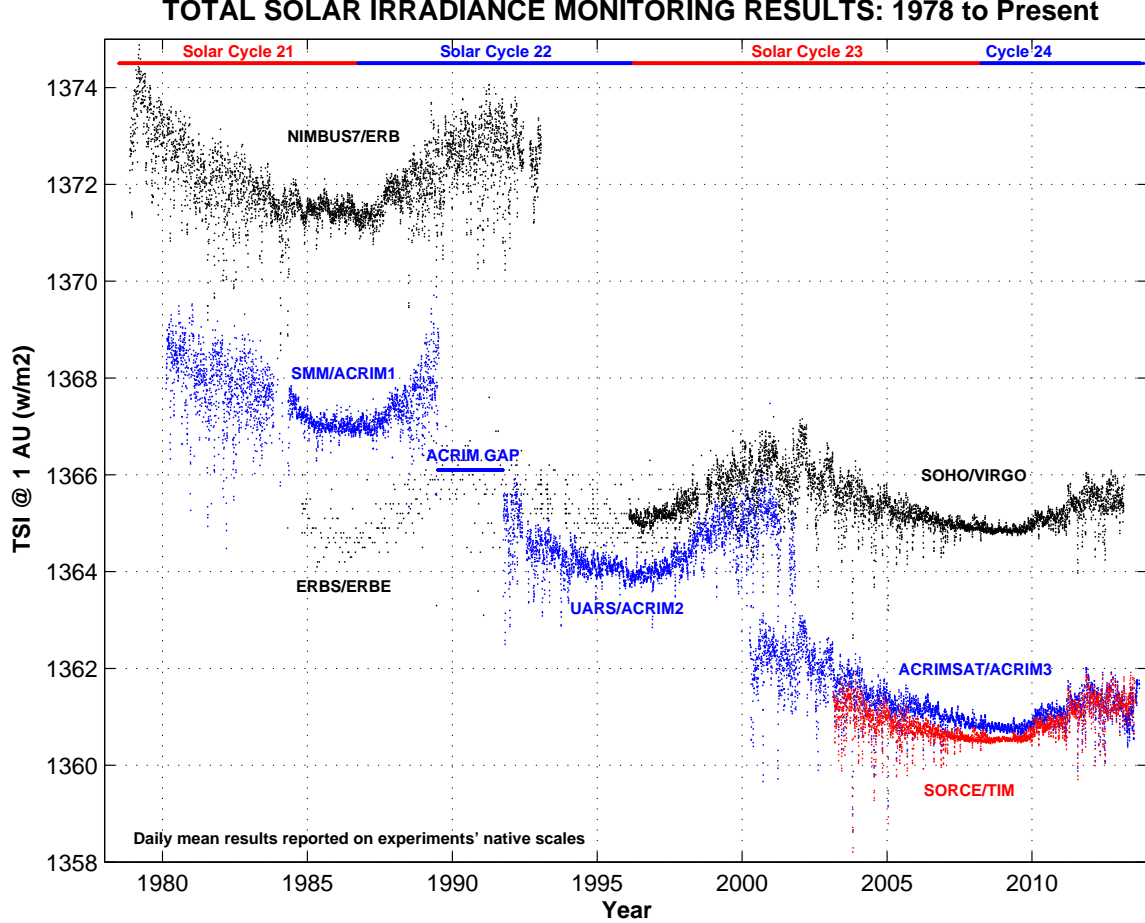


Fig. 1 Total solar irradiance satellite record database.

ACRIM Gap. During the ACRIM Gap ERB results trend upward (linear regression slope = $0.27 \pm 0.04 \text{ Wm}^{-2}/\text{year}$) while ERBE trend downward (linear regression slope = $-0.27 \pm 0.15 \text{ Wm}^{-2}/\text{year}$). This causes the difference between the ACRIM and PMOD TSI trends during solar cycles 21-23. The ACRIM TSI composite uses unaltered ERB results to relate ACRIM1 and ACRIM2 records, while PMOD uses an altered ERB record based on some theoretical model predictions that better agree with the downward trend of the ERBE record during the ACRIM Gap.

In Section 2 we review the hypotheses proposed in the literature about Nimbus7/ERB TSI record during the ACRIM Gap. In sections 3-8 we test these hypotheses by directly comparing the Nimbus7/ERB data sets versus alternative solar data and proxy models. In this process we will study in details the TSI proxy models of Krivova et al. (2007) (KBS07), and Wenzler et al. (2006) (WSKF06) shown in Figure 3. In Appendix A Hoyt (the head of the NASA Nimbus7/ERB science team) explains the accuracy of the ERB record during the ACRIM Gap. Appendix B briefly summarizes the

importance of the TSI satellite composite issue for solar physics and climate change.

2 Review of the PMOD hypotheses about Nimbus7/ERB TSI record

The PMOD composite is constructed using ERB, ACRIM1, ERBE, ACRIM2 and VIRGO results. Some ERB and ACRIM1 published results were modified in the process (Fröhlich and Lean 1998; Fröhlich 2004). These modifications were not based on re-analysis of satellite instrumentation or data but on an effort to conform the satellite TSI record to the predictions of TSI proxy models developed by Lean et al. (1995) and Lee III et al. (1995). These proxy models are statistical regressions containing no physics and cannot be considered to be competitive in accuracy or precision with the satellite TSI observations themselves.

More recently Fröhlich (2006) endeavored to justify alteration of ERB results during its early mission using a theoretical model based on the initial on-orbit

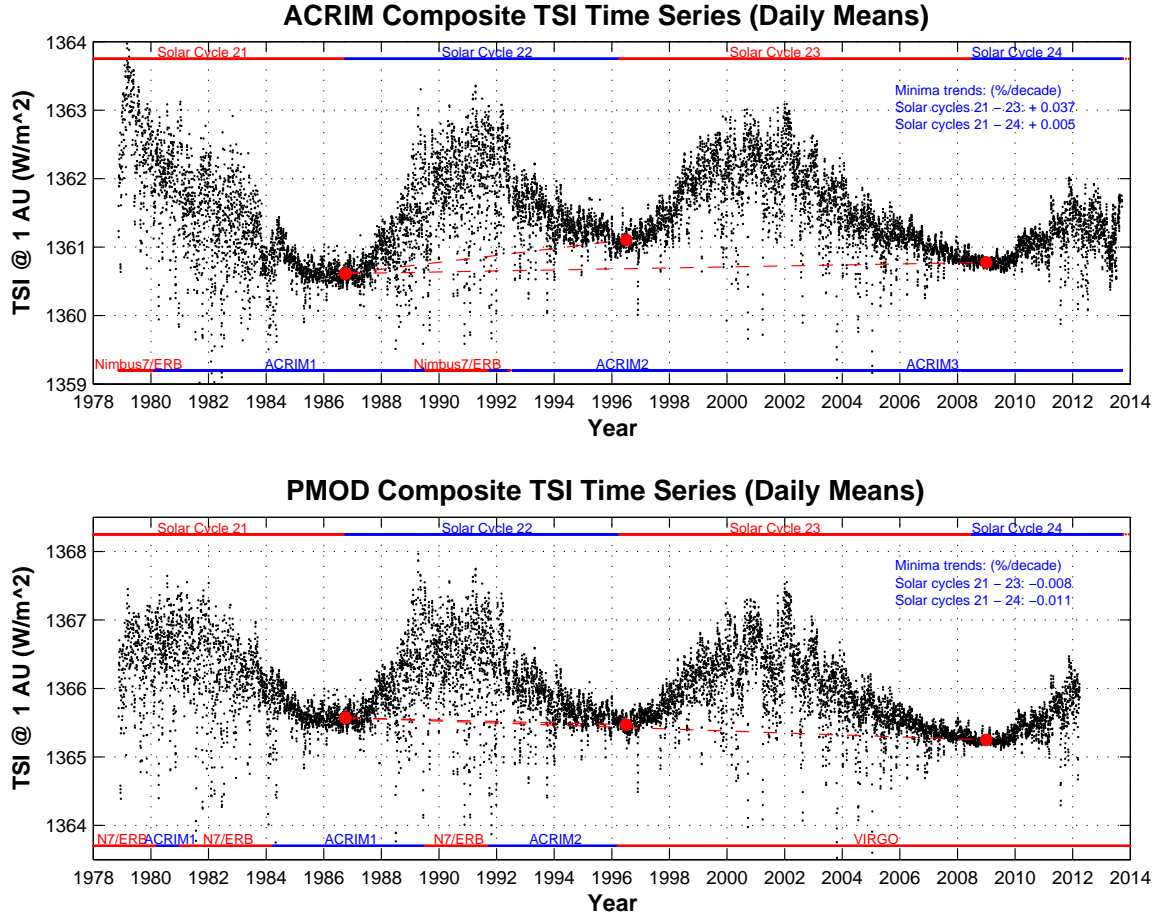


Fig. 2 TSI satellite composites ACRIM and PMOD. Different approaches to bridging the ACRIM Gap result in different trends. The ACRIM composite uses: (1) ERB, ACRIM1, 2 and 3 results published by the experiment science teams; (2) ERB comparisons to bridge the ACRIM Gap; (3) ACRIM3 scale. The PMOD composite uses: ERB, ACRIM1, ACRIM2 and VIRGO results; (2) ERBE comparisons to bridge the ACRIM Gap; (3) Alters published ERB and ACRIM1 results to conform them to TSI proxy models; (4) VIRGO scale.

degradation of VIRGO TSI sensors and the similarity of VIRGO and ERB sensors. However, this approach cannot be used to justify the ERB modifications. It's well known that on-orbit exposure to solar fluxes is the principal cause of sensor degradation and solar exposure was radically different for the VIRGO and ERB missions. VIRGO received constant solar irradiation at its L1 solar orbit because there is no Earth shadow and the shutters for the sensors failed during launch. Irradiation of ERB sensors was far less with solar exposure only 5 minutes each orbit during the three days out of every four it operated in the Nimbus7 Earth orbit. The absorbent surface coating of the VIRGO and ERB sensors exhibited very different degradation with the VIRGO sensors showing the largest degradation (~ 5000 ppm over the mission) yet seen in TSI satellite instrumentation. ERB degradation was more than an order of magnitude less as its results tracked the ACRIM1 experiment during nearly a decade.

The most controversial modification of published ERB results by the PMOD composite was the assignment of a sensitivity shift during the ACRIM Gap. The shift made the ERB 'gap' results agree in scale with the ERBE 'gap' results and caused the decadal TSI trending to agree with the TSI proxy models developed by Lean and Lee III. This was done without any analysis of instrument performance, algorithm update or data processing. It is noteworthy that the scientists most familiar with the ERB experiment and its data, the instrument developer and Principal Investigator, John Hickey, and the NASA ERB science team principal investigator, Douglas Hoyt, both reject the sensitivity increases proposed in Lee and Fröhlich (see Appendix A for a statement written by Hoyt).

Let us review the various attempts to reconcile the ERB and ERBE results during the ACRIM Gap using theoretical models. These have been quite contradictory and deserve special attention.

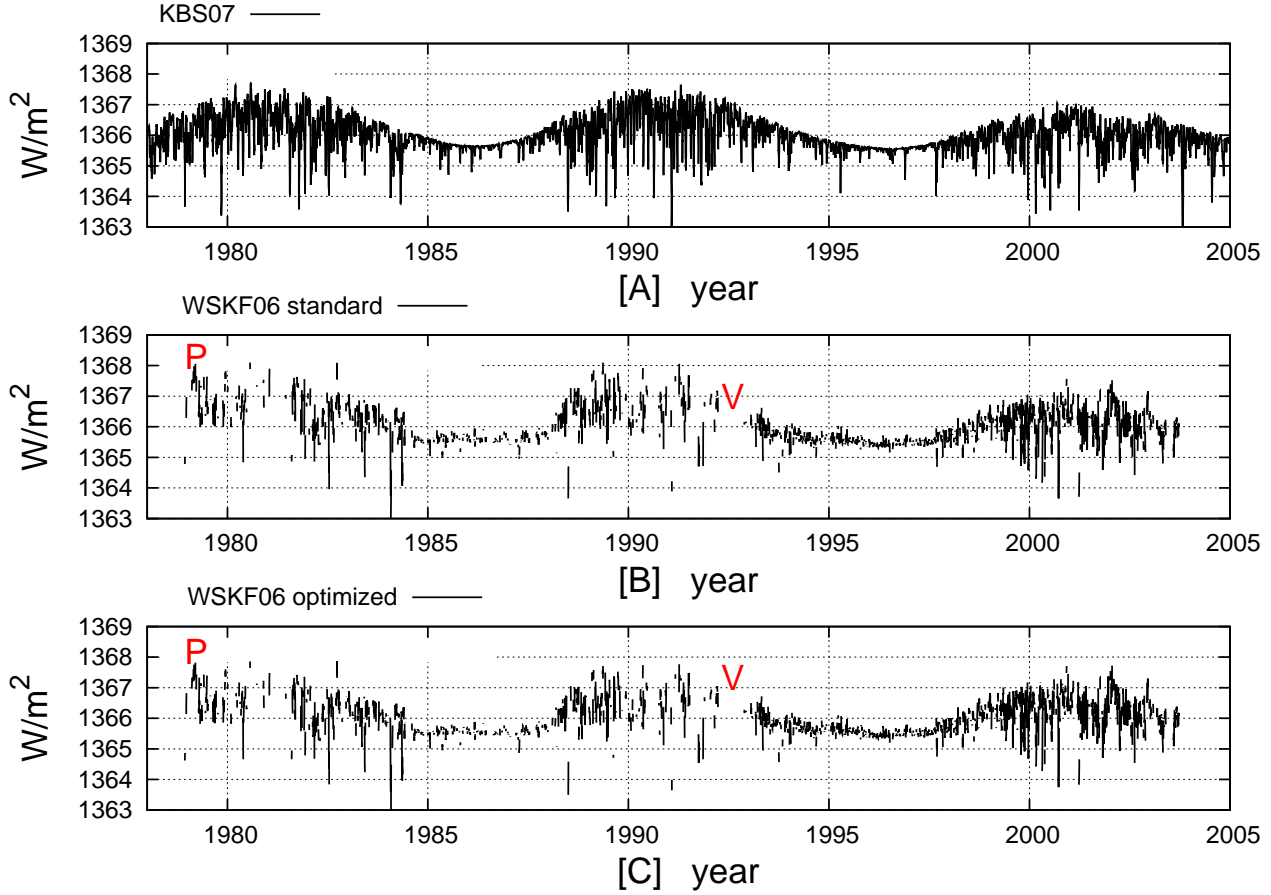


Fig. 3 [A] The Krivova et al. (2007) magnetic field proxy model. [B] Wenzler et al. (2006) (WSKF06) standard surface magnetic field proxy models. [C] Wenzler et al. (2006) (WSKF06) optimized (on PMOD) standard surface magnetic field proxy models. The 1979 peak maximum (red letter “P”) in the WSKF06 models and the lack of available data in 1992 (red letter “V”) that separates NSO-512 (Feb/1/74 to Apr/18/92 and Nov/28/92 to Apr/10/93) and NSO-SPM (Nov/21/92 to Sep/21/03) records calls into question the accuracy of their cross-calibration with the KBS07 model.

1. Lee III et al. (1995) hypothesized that ERB sensors experienced uncorrected sensitivity increases during the ACRIM Gap using the predictions of a simple TSI proxy model regressing the photometric sunspot index (PSI) and the 10.7-cm solar radio flux (F10) against the satellite TSI observations. Lee’s model diverges from ERB results after September 1989 while approximately reproducing the ERBE results. The proxy model’s indication of 0.03% ERB sensitivity increases during both September/1989 and April/1990 was Lee’s rationale for shifting ERB results during the ACRIM Gap downward by 0.06% to agree with ERBE results.
2. Chapmam et al. (1996) developed a TSI proxy model that indicated ERB sensitivity upward shifts of 0.02% and 0.03% in October/1989 and May/1990. They shifted ERB results downward by 0.05% to provide better agreement between ERB and ERBE results during the ACRIM Gap.
3. Fröhlich and Lean (1998) indicated two ERB upward *glitches* in sensitivity occurring exactly on October/1/1989 and May/8/1990). A total downward shift of 0.05% was used to reconcile ERB to ERBE results during the ACRIM Gap.
4. Fröhlich (2004) compared ERB and ERBE results and concluded that ERB experienced a step sensitivity increase of 0.03% on September/29/1989 and a continuing gradual upward linear drift between October/1989 and June/1992. Thus, ERB results had to be first shifted downward on September/29/1989 and then inclined downward until June/1992. The combined effects reconciled ERB and ERBE ACRIM Gap results.
5. Fröhlich (2006) developed another proxy model calibrated against his corrected version of ACRIM1 and ERBE results. He proposed that the similarity of ERB and VIRGO sensors would allow degradation analyses for VIRGO to be applied to ERB results. This approach is called into question by the fact that

the VIRGO sensor has shown unusually large degradation (~ 5000 ppm) during its mission and there is no evidence ERB experienced a similar effect of comparable magnitude. Lastly, degradation is directly tied to the amount of exposure to the sun and this is very different for the ERBE and VIRGO PMO6-A sensor.

3 Direct analysis of PMOD hypothesis of an ERB sensitivity increase during the ACRIM Gap

Figure 4 shows our analysis of the latest Fröhlich (2006) revision of ERB results. The difference between published ERB results and the PMOD composite during the ACRIM Gap is minimized by a step function sensitivity change of $+0.034\%$ (0.47 W/m^2) on September/29/1989 followed by a linear upward drift of $0.01\%/year$ from October/1989 through mid-1992. During the ACRIM Gap Fröhlich (2006) corrects the ERB results by about 0.063% (0.86 W/m^2), shifting them downward to agree with ERBE (see the detailed discussion in Scafetta 2011). This corresponded also to the predictions of Lean's TSI proxy model used for the previous version of the PMOD composite (Fröhlich and Lean 1998; Fröhlich 2004). The direct consequence of Fröhlich's revision is that the PMOD TSI composite shows no significant trending between the 1986 and 1996 solar minima.

Fröhlich did not make original computations using ERB flight data or indicate the statistical uncertainty associated with his alteration of the TSI experimental results originally published by the ERB science team. The PMOD TSI composite data ¹ reports TSI daily values with four decimal digits of precision. The TSI values of the original satellite records have, on average, only two decimal digits of precision. Clearly PMOD misrepresents the statistical significance of its data which calls into question the validity of PMOD trending.

4 ACRIM Gap and the line of sight solar magnetic field strength (SMFS) measurements

A first order resolution of the ACRIM Gap issue can be made by observing that the ERB TSI increase during the gap conforms to the Solar Magnetic Activity/TSI (SMA/TSI) paradigm; a positive correlation between

TSI and solar magnetic activity discovered by satellite experiments during the 1980's (Willson and Hudson 1991; Willson 1997). The SMA/TSI paradigm holds on time scales longer than a solar rotation and approximately correlates with the quasi 11-year TSI cycle. It has been validated by all experimental components of the set of TSI satellite monitoring observations to date.

The SMA/TSI paradigm would be confirmed by the upward trend of the daily line of sight solar magnetic field strength (SMFS) measurements shown in Figure 5B during the ACRIM Gap. During the ACRIM Gap ERB results trend upward with the SMFS record and conform to the SMFS/TSI paradigm. ERBE are anti-correlated, trending downward (compare Figures 5A and 5B). ERB results should therefore be considered the most likely correct representation of TSI trending during the ACRIM Gap. Consequently, the ACRIM TSI composite is the most likely correct representation of the decadal TSI trend during solar cycles 21-23.

The most probable explanation for the ERBE negative trend correlation with the SMFS during the ACRIM Gap could be uncorrected sensor degradation. Rapid degradation of TSI sensors is commonly observed during initial exposures to the enhanced UV fluxes that occur during periods of maximum solar magnetic activity (Willson and Mordvinov 2003). During solar maxima extreme UV photon energy flux is about two times larger than during solar cycle minima (Lean 2005) and sensor degradation can occur much faster.

Sensor degradation on most experiments saturates eventually, becoming asymptotic after prolonged exposure to solar UV fluxes. The high and rising level of solar magnetic activity during solar cycle 22 that occurred during the ACRIM Gap was the first exposure of ERBE to enhanced UV radiation. The solar cycle 22 maximum was the second exposure for ERB, whose mission began in 1978 just before the maximum activity period of solar cycle 21, and whose degradation had likely already reached or was approaching its asymptote after 1985.

We note that TSI proxies, such as the sunspot number, the F10.7 radio flux, and the Ca-II, Mg-II and He-I chromospheric lines that address certain features and wavelength regions of the solar spectrum, do not show a consistent upward trend during the ACRIM Gap (Fox 2004, figures 12 and 13). However, SMFS, the solar magnetic flux index, should provide a more robust and specific proxy for solar magnetic activity and TSI. Addressing the ACRIM GAP TSI trending issue using solar proxies that address specific wavelength ranges is a controversial approach. A more detailed investigation using TSI data and solar magnetic activity proxy data and models is required, and this is our approach.

¹<ftp://ftp.pmodwrc.ch/pub/data/irradiance/composite/DataPlots/>

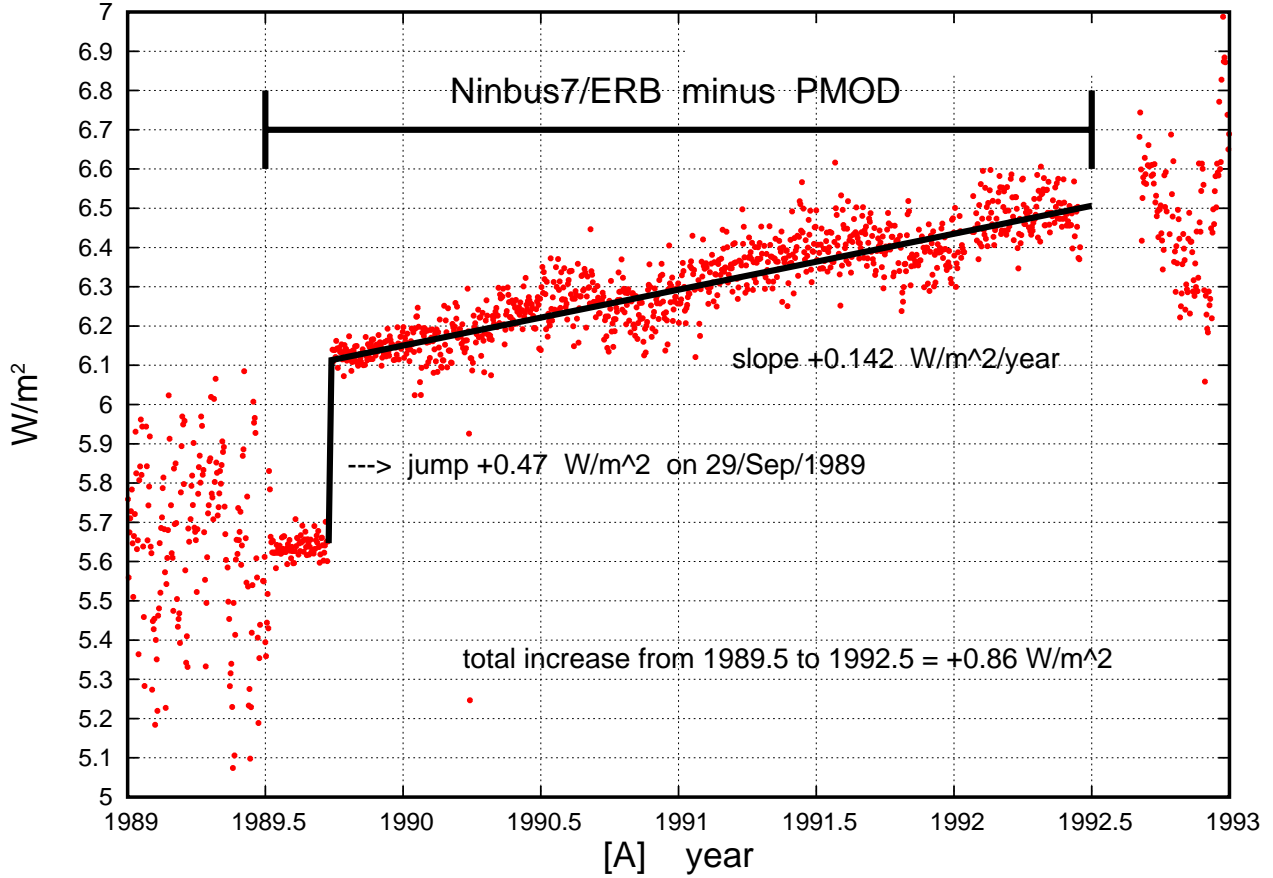


Fig. 4 The PMOD corrections to the ERB record during the ACRIM Gap (1989.5-1992.5) shown as the residual function Eq. 1 between Nimbus7/ERB results and the PMOD TSI composite model.

5 The Sep/29/1989 Nimbus7/ERB ‘glitch’ hypothesis

We will now examine the ERB ‘glitch’ hypothesis of Lee III et al. (1995) and Fröhlich (2006) hypothesized to have occurred on Sep/29/1989. Their ERB ‘glitch’ was derived using a direct comparison of ERB record and of a proxy model calibrated on ERBE records. Their claim is that ERB sensors exhibited a $\sim 0.4 \text{ W/m}^2$ sudden increase of sensitivity following a three-day instrument power down (Sep. 25-28, 1989), implying that sensor properties changed. Figure 6 shows the difference between ERB and ERBE results for days between Jan/01/1989 and Jun/30/1990 when both experiments had solar observations. The relevant TSI values are reported in Table 1.

Figure 6 clearly shows that ERB and ERBE diverge by $\sim 0.5 \text{ W/m}^2$ over this 1.5 year period. This divergence did not occur as a step function during the three-day power-down of September 25-28, as postulated by Lee and Fröhlich. During the period Jan/1989 to the end of Sep/1989 the mean of the difference between the two records is $-6.26 \pm 0.35 \text{ W/m}^2$. During the period

Nov/23/1989 to Jun/20/1990 the mean of the difference between the two records is $-6.74 \pm 0.32 \text{ W/m}^2$. The values on Oct/11, Oct/25 and Nov/08 statistically agree with the previous Jan/1989-Sep/1989 trend 23 times better than with the ensuing Nov/23/1989-Jun/20/1990 trend: their mean value is $-6.23 \pm 0.20 \text{ W/m}^2$. See also the discussion made in Scafetta (2011, figure 7) that also highlights a rapid, but gradual divergence between Nimbus7/ERB and ERBS/ERBE during October and November 1989 that contrasts with the sudden one-day glitch shift claimed by PMOD on September 29, 1989.

Thus, the experimental evidence indicates that ERB and ERBE results changed in November 1989, not at the end of September. This result questions the single most important PMOD composite assumption that produces different 1980-2000 trending from the ACRIM composite. It also supports Hoyt’s statement (see the Appendix): “*The calibrations before and after the September shutdown gave no indication of any change in the sensitivity of the radiometer.*”

An ERBE sensitivity reduction at about that time may have had numerous causes. For example, during

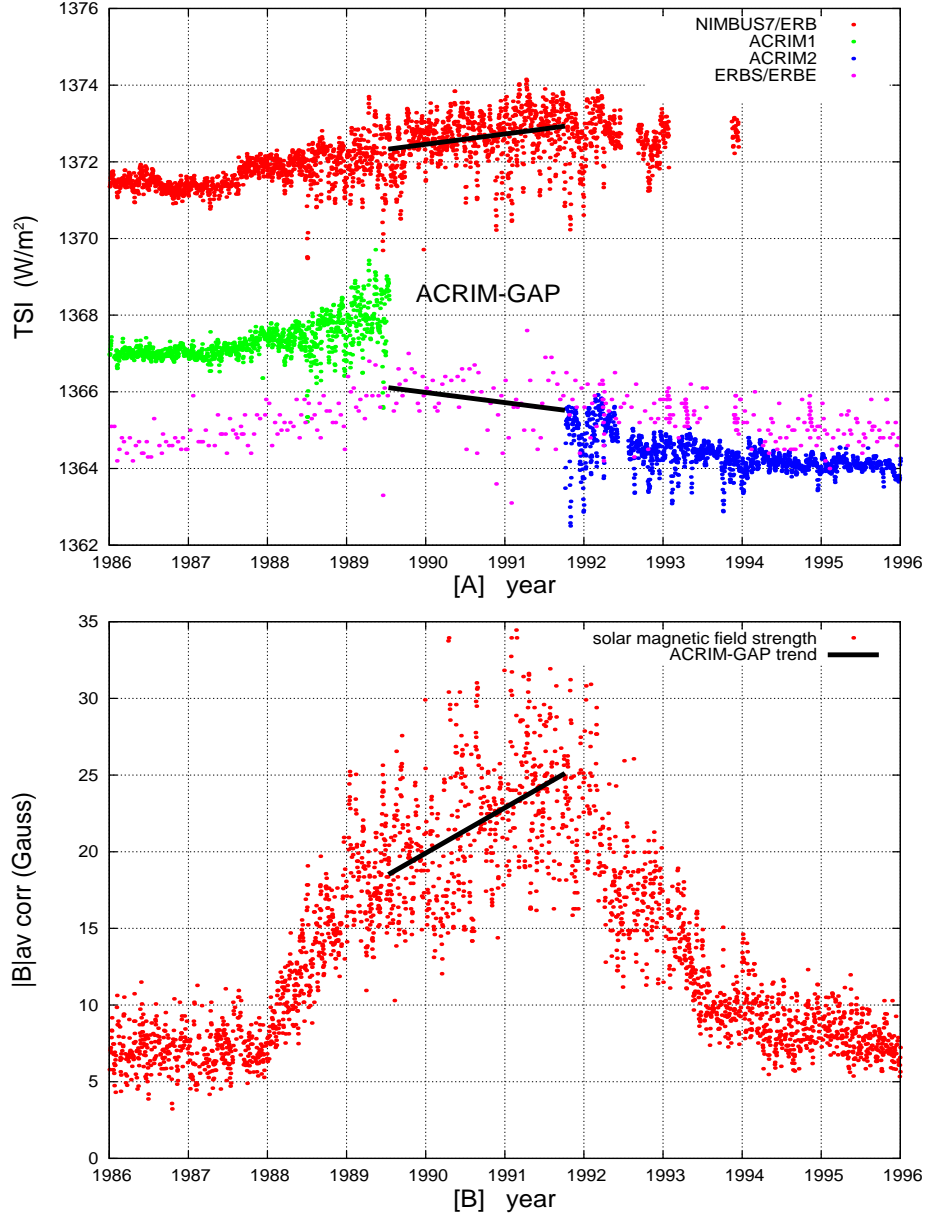


Fig. 5 [A] ACRIM1, ACRIM2, Nimbus7/ERB and ERBS/ERBE original records during solar cycle 22. [B] The solar magnetic field strength (National Solar Observatory/Kitt Peak Data Archives: <ftp://nsokp.nso.edu/kpvt/daily/stats/mag.dat>). During the ACRIM Gap (1989.53-1991.76) the data clearly show an upward trend (black segment) in the solar magnetic index (linear regression slope = $3.0 \pm 0.3 \text{ Gauss/year}$) that is consistent with the TSI upward trend of Nimbus7/ERB record (linear regression slope = $0.27 \pm 0.04 \text{ Wm}^{-2}/\text{year}$) but not with the TSI downward trend of ERBS/ERBE record (linear regression slope = $-0.27 \pm 0.15 \text{ Wm}^{-2}/\text{year}$).

1989 there was an exceptionally high rate of increase of solar activity due to the fact the Sun was approaching the maximum of solar cycle 22. The ERBE-ERB divergence occurred during November 1989 and this period coincided, for example, with an exceptionally high value of the solar flare index (SFI) whose monthly means are

indicate in the bottom of Figure 6. The SFI maximum of the year occurred on Oct/19/1989 (SFI = 89) and the SFI average for November was higher (mean SFI = 22.5) than the previous months. Thus, the ERB-ERBE divergence during that period could have been caused by a rapid degradation of ERBE sensors by enhanced

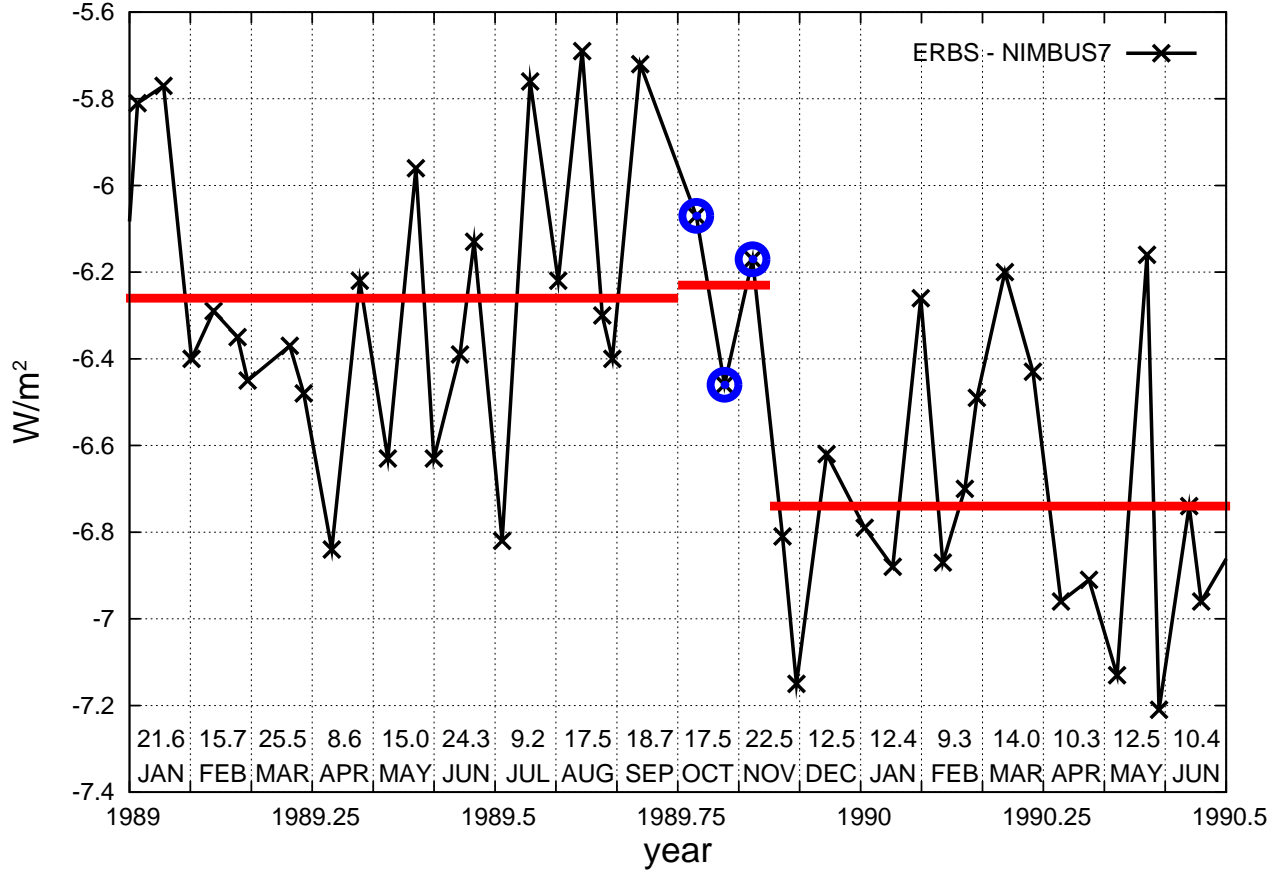


Fig. 6 Residual function Eq. 1 between ERBS/ERBE and Nimbus7/ERB results: see Table 1. The two records diverge mostly in November, not at the end of September. The blue circle events in October and November 1989 are statistically compatible with the values before the end-of-September ERB ‘power-down’ event. The red segments are mean values during the corresponding periods. At the bottom of the figure the solar flare index (SFI) activity is reported showing a peak during Nov/1989: SFI data from <ftp://ftp.ngdc.noaa.gov/STP/space-weather/solar-data/solar-features/solar-flares/index/comprehensive-flare-index/documentation/cfi-{}n>

UV solar fluxes as the Sun entered in its maximum level of activity. As explained in Sections 4 and 5, rapid TSI sensor degradation occurs during their first exposure to the enhanced short wavelength fluxes of solar maximum periods. This was the first solar maximum experienced by ERBE but the second by ERB, which likely had reached or was near its asymptotic degradation level. Solar pointing issues could also have occurred.

There may be other physical explanations for the ERB-ERBE divergence during the ACRIM Gap as discussed in section 4. However the Sep/1989 Nimbus7/ERB three-day ‘glitch’ hypothesis proposed by Lee and Fröhlich is not supported by the experimental evidence reported in Figure 6.

6 ACRIM - PMOD - KBS07 comparison

Scafetta and Willson (2009) showed that the TSI proxy model of Krivova et al. (2007) is not compatible with an

ERB sensitivity increase in September 1989. This was demonstrated by showing that bridging the ACRIM Gap using KBS07 instead of ERB produces a 1980-2000 upward trend very similar to that found by the ACRIM TSI composite. Here, we confirm and extend this result with an alternative methodology.

In this section and in the following we study dynamical pattern divergences between the TSI satellite records and TSI proxy models. If the function $TSI_{sat}(t)$ represents a TSI experimental satellite record during a given period, and the function $TSI_{mod}(t)$ represents a TSI proxy model supposed to reconstruct the experimental record, then the residual function

$$f(t) = TSI_{sat}(t) - TSI_{mod}(t) \quad (1)$$

can be computed. Clearly if the proxy model well reproduces the experimental result within the given time interval, then the function $f(t)$ should be compatible

date	ERBE W/m^2	ERB W/m^2	diff W/m^2	date	ERBE W/m^2	ERB W/m^2	diff W/m^2
89/01/05	1366.4	1372.21	-5.81	89/10/11	1367.0	1373.07	-6.07
89/01/18	1366.0	1371.77	-5.77	89/10/25	1366.6	1373.06	-6.46
89/02/01	1366.1	1372.50	-6.40	89/11/08	1366.5	1372.67	-6.17
89/02/12	1365.6	1371.89	-6.29	89/11/23	1365.7	1372.51	-6.81
89/02/24	1365.5	1371.85	-6.35	89/11/30	1365.5	1372.65	-7.15
89/03/01	1365.8	1372.25	-6.45	89/12/15	1366.4	1373.02	-6.62
89/03/22	1365.3	1371.67	-6.37	89/12/20	1365.9	1369.71	-3.81*
89/03/29	1365.9	1372.38	-6.48	90/01/03	1366.1	1372.89	-6.79
89/04/12	1366.8	1373.64	-6.84	90/01/17	1366.0	1372.88	-6.88
89/04/26	1365.9	1372.12	-6.22	90/01/31	1366.3	1372.56	-6.26
89/05/10	1366.7	1373.33	-6.63	90/02/11	1365.6	1372.47	-6.87
89/05/24	1365.9	1371.86	-5.96	90/02/22	1365.5	1372.20	-6.70
89/06/02	1365.6	1372.23	-6.63	90/02/28	1365.7	1372.19	-6.49
89/06/15	1363.3	1369.69	-6.39	90/03/14	1366.2	1372.40	-6.20
89/06/22	1366.1	1372.23	-6.13	90/03/28	1366.4	1372.83	-6.43
89/07/06	1365.9	1372.72	-6.82	90/04/11	1365.9	1372.86	-6.96
89/07/20	1366.1	1371.86	-5.76	90/04/25	1366.3	1373.21	-6.91
89/08/03	1365.5	1371.72	-6.22	90/05/09	1365.9	1373.03	-7.13
89/08/15	1365.7	1371.39	-5.69	90/05/24	1366.4	1372.56	-6.16
89/08/25	1366.6	1372.90	-6.30	90/05/30	1365.6	1372.81	-7.21
89/08/30	1366.2	1372.60	-6.40	90/06/14	1366.6	1373.34	-6.74
89/09/13	1365.9	1371.62	-5.72	90/06/20	1366.3	1373.26	-6.96

Table 1 TSI data from ERBS/ERBE and Nimbus7/ERB and their difference, which is depicted in Figure 6. *The value on December 20, 1989 is excluded because the ERB value is highly uncertain. Data from <ftp://ftp.ngdc.noaa.gov/STP/SOLAR-{}DATA/SOLAR-{}IRRADIANCE/>

with stationary random noise. However, if statistically significant trends are observed in $f(t)$ the proxy model is not capable of reproducing the experimental results. The use of this methodology to study TSI records is common in scientific literature (compare with: Fröhlich 2004, 2006, 2012).

Figure 7 shows the residual function (Eq. 1) between ERB and KBS07 (top panel) and between PMOD and KBS07 (bottom panel). Clearly the KBS07 model shows the same trends as ERB both before and after 09/29/1989. However, KBS07 shows a significant shift of $0.45 W/m^2$ relative to PMOD. This is caused by the putative PMOD sensitivity change ($+0.033\%$) applied to the ERB results for that day. Thus, the KBS07 model shows the same upward trend as the original ERB record from 1988.5 to 1991. The ERB ACRIM Gap sensitivity increases proposed by Lee III et al. (1995), Chapmam et al. (1996), Fröhlich and Lean (1998), Fröhlich (2004) and Fröhlich (2006) are incompatible with the KBS07 proxy model.

Krivova et al. (2009) criticism of a previous analysis of the ACRIM Gap by Scafetta and Willson (2009) claimed that the KBS07 model was only useful for

longer periods than the ACRIM Gap and lacked sufficient resolution to reproduce trends as short as 1-2 year periods. To show Krivova's claims are incorrect we employ an alternative methodology that excludes the ACRIM Gap period and ACRIM1, ACRIM2 and PMOD are directly compared against KBS07 during the longer near decadal length periods pre-gap: 1980-1989.5 and post-gap: 1992.5-2001.

Figure 8 shows the residual function (Eq. 1) between ACRIM1-ACRIM2 results and KBS07 (panels A and B), and between PMOD and KBS07 (panels C and D). The results are evidently non stationary. KBS07 does not capture the TSI decadal dynamics well. Second order polynomials (red curves) are used to capture, at the first and second order of precision, the discrepancies between experimental and the proxy model records' decadal trends and the curvature of the 11-year solar cycles. Figure 8 clearly shows that on the decadal scale KBS07 underestimates the amplitude of the solar cycle between 1980 and 1989 (that is, the polynomial fits of the residual functions present positive quadratic coefficients) and misses an upward trend from 1992 to 2000

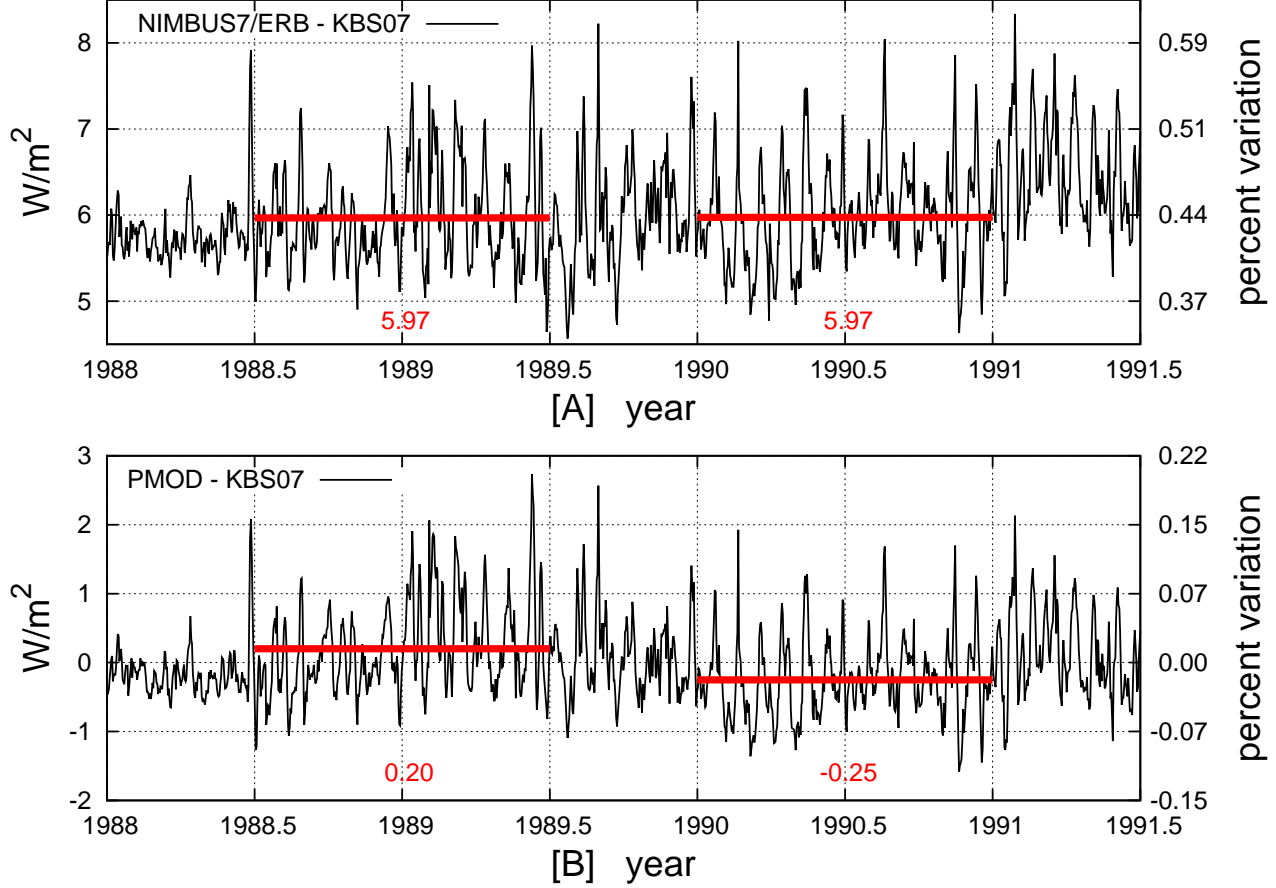


Fig. 7 Residual between ERB, PMOD and the KBS07. [A] residual function Eq. 1 between ERB results and the KBS07 proxy model proposed by Krivova et al. (2007). [B] residual function Eq. 1 between the PMOD composite and KBS07. Red segments and red values indicate the relative levels during the period 1988.5-1989.5 and 1990-1991 (before and after Fröhlich’s hypothesized ERB-glitch on 09/29/89). The relative average values during 1988.5-1989.5 and 1990-1991 show that KBS07 does not support the 09/29/89 ERB sensitivity step increase proposed by Fröhlich.

(that is, the polynomial fits of the residual functions present positive linear coefficients).

Figure 9 shows a KBS07 model after empirical adjustments during 1980-1989.5 and 1992.5-2001. The adjustments are designed to reproduce both the trending and the amplitude of the 11-year solar cycles (as shown in ACRIM1-ACRIM2 and PMOD TSI records) by using as a guide the second order polynomial fit functions depicted in Figure 8. For example, if $p(t)$ is the second order polynomial fit of the residual function (Eq. 1) shown in Figure 8 in a specific period 1980-1990 or 1991.5-2000, the KBS07 model is corrected as $KBS07 + p(t)$. This implies that: (1) the amplitude of the KBS07 11-year solar cycle from 1980 to 1989 KBS07 is corrected by increasing its amplitude by the amount shown in Figure 8A and 8C, respectively, which lowers the TSI minimum in 1986; and (2) from 1992 to 2000 KBS07 is corrected by adding the upward trending by the amount shown in Figures 8B and 8D, respectively, which raises the TSI minimum in 1996. The final re-

sult makes KBS07 better resemble the dynamical patterns of ACRIM1 and ACRIM2 records (Figure 9A) and of the PMOD TSI composite (Figure 9B) outside the ACRIM gap. The KBS07 data during the ACRIM Gap are left unaltered. Figure 9 shows that once the KBS07 model is adjusted to better fit the data, a TSI upward trend emerges in both KBS07-adjusted composites during 1980-2000. This upward trend resembles the upward trend of the original ACRIM TSI composite.

Thus, the multi-decadal agreement between the original KBS07 model and PMOD derived by Krivova et al. (2007) appears coincidental. It’s likely an artifact of the failure of KBS07 to reproduce the correct trending and amplitude of the solar cycles from 1980 to 2001. The ACRIM1 and ACRIM2 results provide the best available estimates of TSI during this period. This result supports the analysis of Scafetta and Willson (2009) and validates the ACRIM TSI composite.

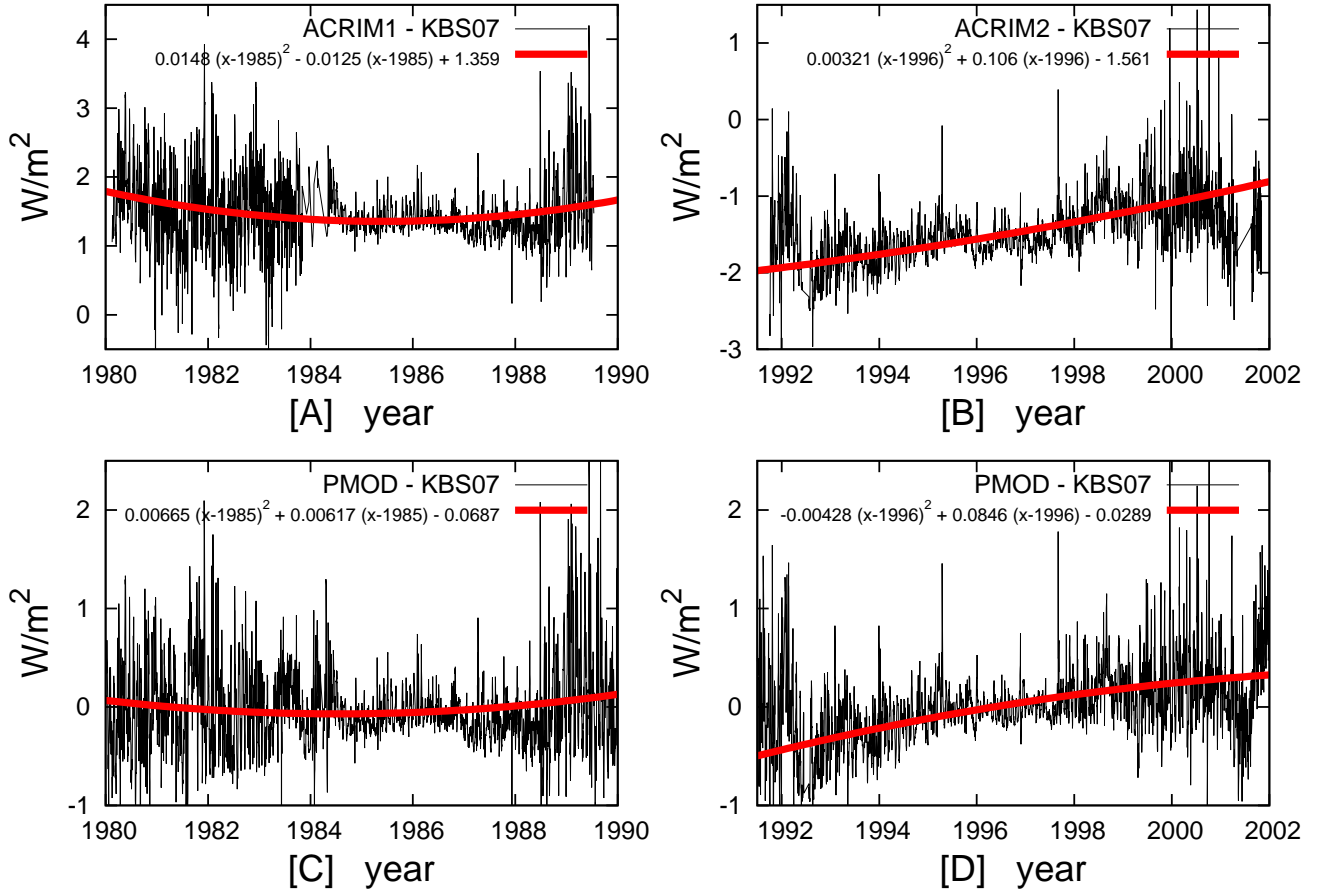


Fig. 8 Residual function Eq. 1 of ACRIM1, ACRIM2 and PMOD with the KBS07 TSI proxy model. The black curves are parabolic fits during 1980-1989.5 and 1992.5-2001.

7 ERB - ACRIM1 - PMOD - WFKS06 comparison

We will now compare the TSI data against the WFKS06 solar magnetic field strength models (Wenzler et al. 2006, 2009). Krivova et al. (2009) claims that they are more accurate than KBS07 on short time scales and agree with PMOD ACRIM gap hypothesis.

In addition to the ACRIM Gap ERB TSI data, Fröhlich altered other TSI published results for the ERB and ACRIM1 before 1985 (Fröhlich and Lean 1998; Fröhlich 2004, 2006, 2012): (1) the early solar cycle 21 peak of ERB results were altered to agree with Lean's TSI proxy model; (2) ACRIM1 results were altered to include Fröhlich's speculation about uncorrected degradation during its first year of operation; (3) Fröhlich used his altered version of published ERB results instead of ACRIM1 during 1981-1984, claiming that ACRIM1 results were compromised during the SMM spin mode. None of these adjustments are supported by Fröhlich with physical arguments, algorithm changes or computations using original data and all are disputed by the ERB science team (see the Hoyt's state-

ment in the Appendix) and the ACRIM1 science team (which is represented here by ACRIM PI Willson).

WSKF06 TSI proxy reconstructions (Wenzler et al. 2006) (see figure 3B and 3C) are based on two inhomogeneous records of the National Solar Observatory (NSO): 1734 data points are from the 512-channel Diode Array Magnetograph (NSO-512) which covers the period from Feb/1/74 to Apr/18/92 and from Nov/28/92 to Apr/10/93) and 2055 data points from the Kitt Peak Spectromagnetograph (NSO-SPM) which covers the period from Nov/21/92 to Sep/21/03). Only 45 days of NSO-512 data (Nov/28/92 to Apr/10/93) are used for the cross calibration between NSO-SPM and NSO-512 data. Thus, NSO-512 and NSO-SPM records were collected using different instrumentation and their composite in 1992 includes a significant cross-calibration uncertainty as a result.

Wenzler et al. (2006, figure 6) shows the histogram-equalizing curves for 22 individual days calculated with NSO-SPM and NSO-512 magnetograms used to cross-calibrate the two records and construct the WSKF06 composite. This figure clearly suggests a nonlinear relationship between these two magnetogram records. De-

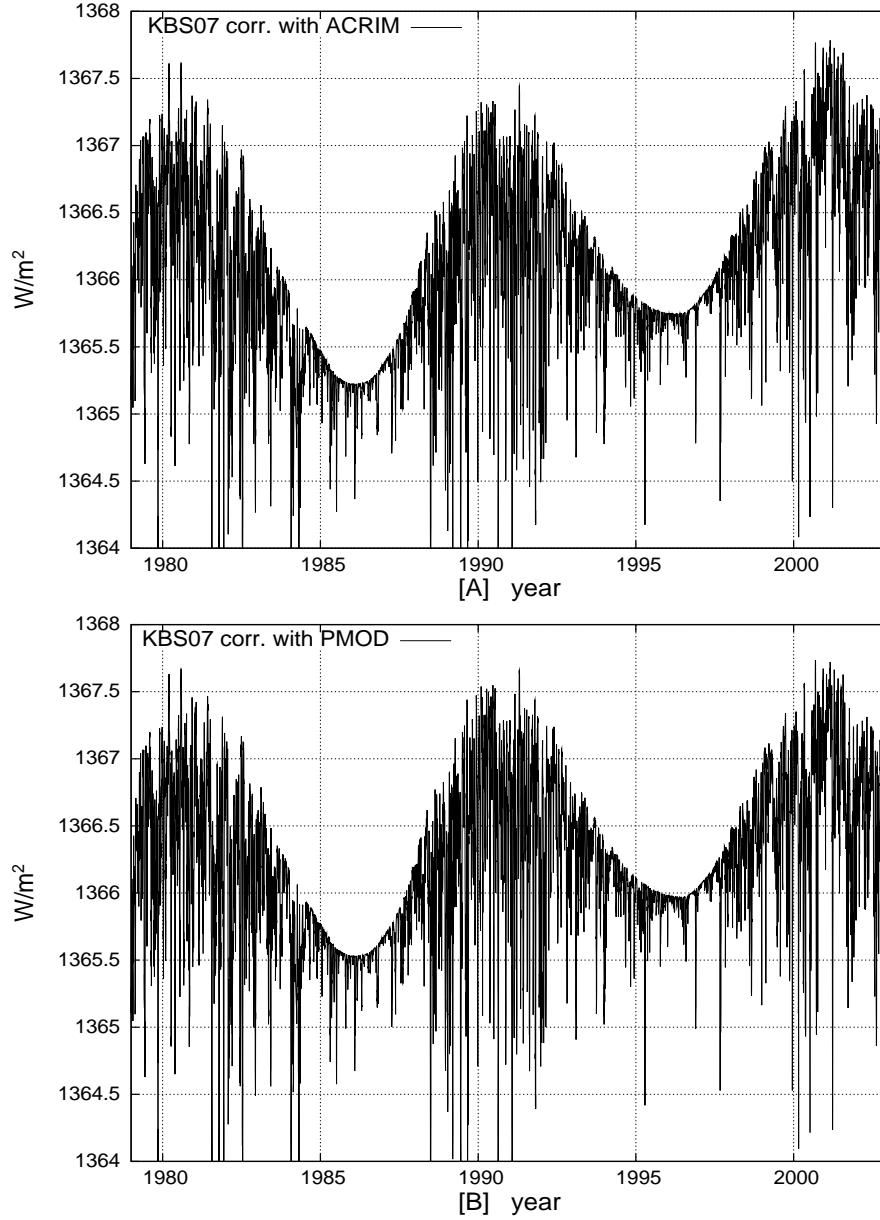


Fig. 9 Top: KBS07 recalibrated on the ACRIM1 and ACRIM2 TSI records. Bottom: KBS07 recalibrated on the PMOD TSI composite. The calibration covers only the periods 1980-1989.5 and 1992.5-2001. The TSI 1980-2000 trends of both are similar to the trend in the ACRIM composite.

spite this Wenzler et al. (2006) simplified their analysis by assuming linearity between the two data sets and proposed two solutions: (1) a *standard* model using the accepted value of the cross-correlation factor $f = 1.46$ between NSO-512 and NSO-SPM and (2) an *optimized* model using a cross-correlation factor $f = 1.63$ specifically chosen to reproduce a minimum to minimum trend agreeing with the PMOD composite. ACRIM's trend can also be reproduced by choosing a factor of $f = 2.0$,

which Wenzler et al. (2009) rejected as a high-end value for f .

It is clear that using this model to discriminate between ACRIM and PMOD trending between 1980 and 2000 could not produce unambiguous results due mostly to the cross-calibration uncertainty problem between NSO-512 and NSO-SPM. Our approach is to compare WSKF06 directly with the satellite observations which

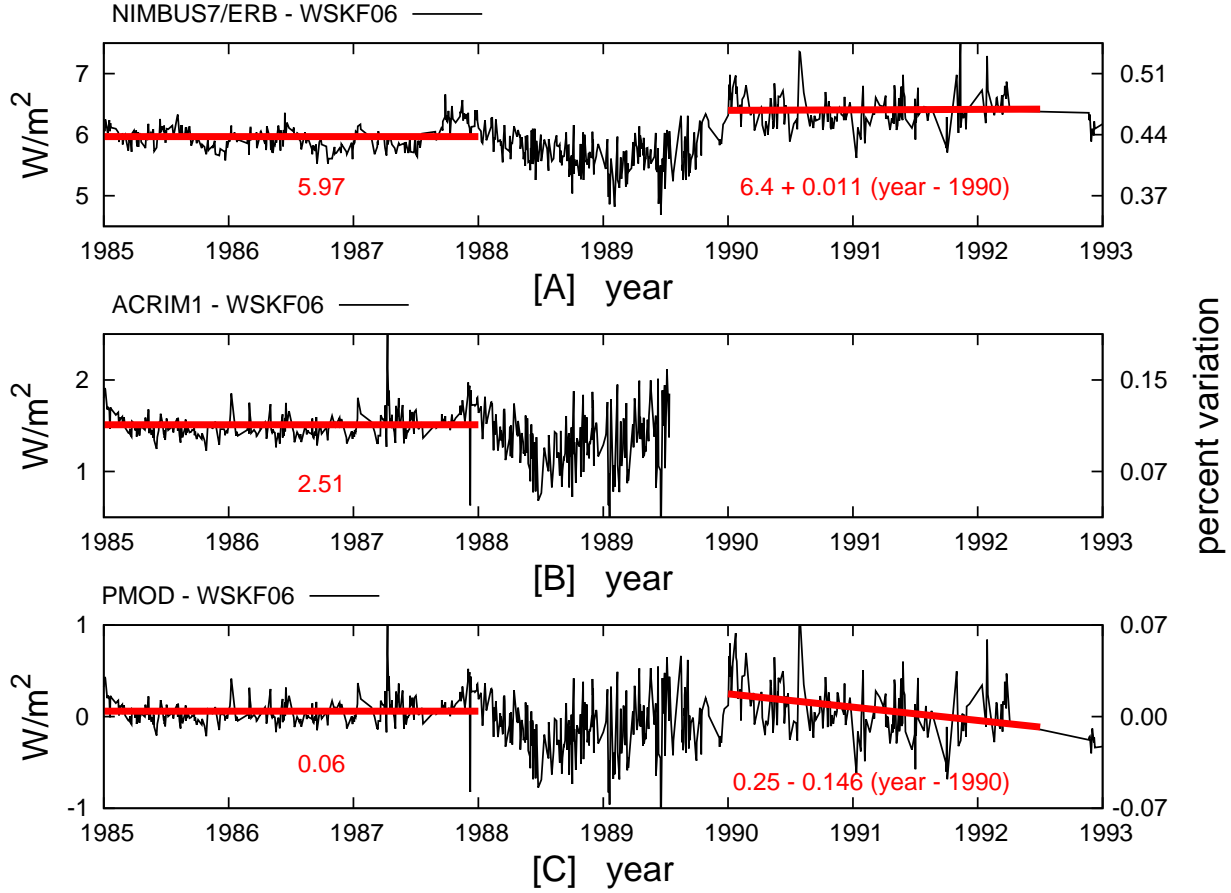


Fig. 10 Residual function Eq. 1 between: [A] ERB and WSKF06; [B] ACRIM1 and WSKF06; [C] PMOD and WSKF06. It is used the WSKF06 optimum model (Wenzler et al. 2006).

adds information that may help identify the correct TSI composite.

We make use of the residual function given by Eq. 1 between ERB, ACRIM1 and PMOD results as shown in Figures 10 and 11. The predictions of the WSKF06 *optimum* and *standard* proxy model results are shown in Figures 10 and 11, respectively. During this period (prior to 1992) WSKF06 is comprised of only the NSO-512 record, which removes the cross-calibration uncertainty problem between NSO-512 and NSO-SPM discussed above.

7.1 Period 1978-1980: the Nimbus7/ERB 1979 peak

Let us now analyze alternative periods. The original ERB results show a peak during 1979.1-1979.3 that Fröhlich and Lean (1998) reduce in their PMOD composite to agree with the prediction of Lean's proxy model. Figure 12 compares the WSKF06 model and PMOD composite during the period 1979.5 to 1979.6. WSKF06 presents a TSI peak in 1979.2 about 0.8 W/m^2 higher than the PMOD level, although its amplitude is lower than that of the original ERB record

(compare with Figure 11). Fröhlich's reduction appears to be excessive since WSKF06 in Figure 12 also shows a TSI peak in early 1979. It's worthwhile mentioning that the ERB TSI peak in early 1979 is very similar to a pronounced peak during the maximum of solar cycle 23 (1998-2004) that was observed by both ACRIM2, ACRIM3 and VIRGO (see Figure 1) during comparable solar magnetic activity. Recently, Scafetta and Willson (2013b) showed that these TSI peaks are correlated with the 1.092-year conjunction cycle between Jupiter and Earth, fitting a pattern of planetary modulation of solar activity.

The comparison with WSKF06 indicates that before 1980 ERB results can require some adjustment for possible uncorrected degradation and a change of the orbital orientation as proposed by Fröhlich (2004, 2006). The adjustments to ERB results made by Fröhlich in the PMOD composite are too large since they remove a TSI peak near 1979.2 that is predicted by WSKF06 and present in the original ERB results.

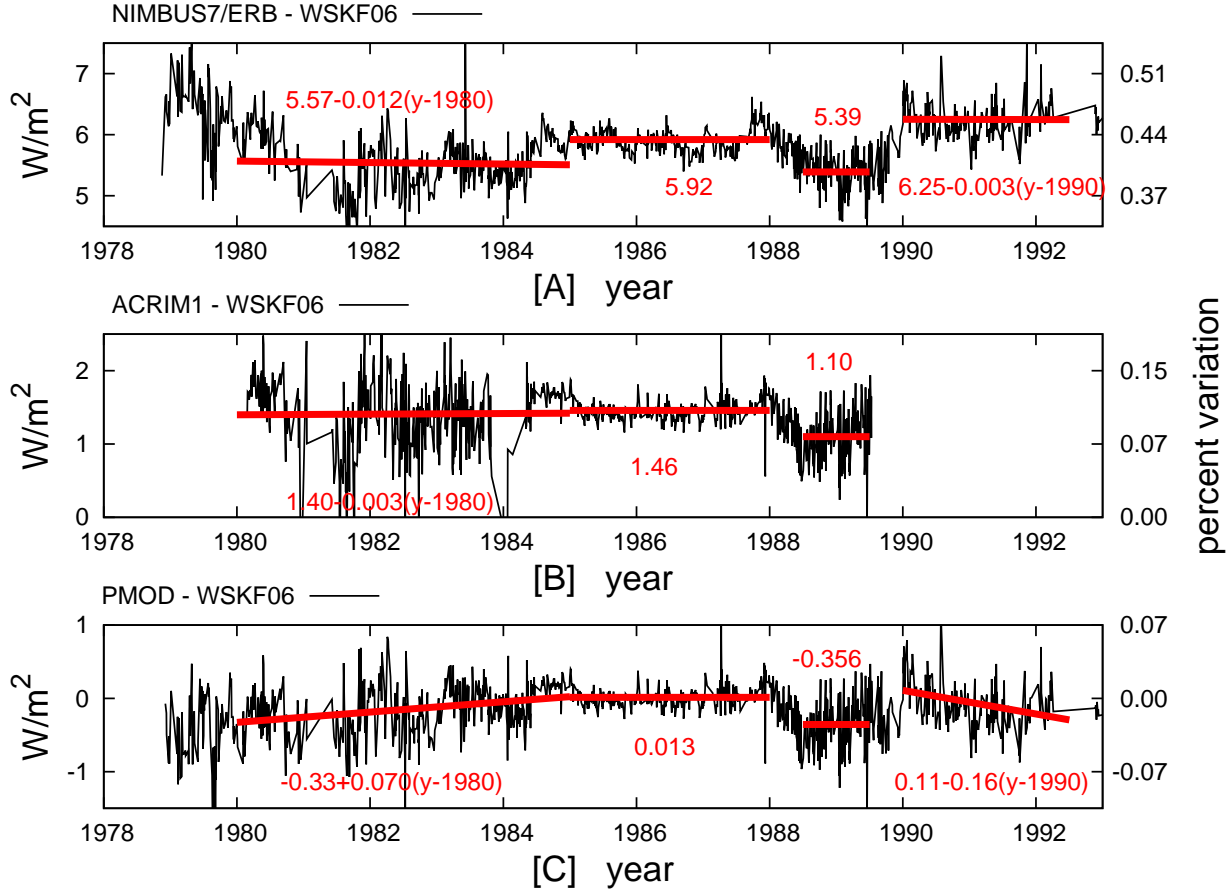


Fig. 11 Residual function Eq. 1 between: [A] ERB and WSKF06; [B] ACRIM1 and WSKF06; [C] PMOD and WSKF06. It is used the WSKF06 standard model (Wenzler et al. 2006).

7.2 Period 1980-1985: the ACRIM1 spin mode

The trend agreement between ACRIM1 and the WSKF06 proxy model during 1980 to 1985 is excellent, as seen in Figure 11. The linear fit of the residual function (Eq. 1) between the two records produces a slope statistically equivalent to zero ($-0.003 \pm 0.02 \text{ Wm}^{-2}/\text{year}$), which indicates statistical stationarity. The comparison with ERB also yields a slope statistically equivalent to zero ($-0.012 \pm 0.015 \text{ Wm}^{-2}/\text{year}$). In contrast, a poor trend agreement is found between PMOD and WSKF06 as measured by the statistically significant positive slope ($+0.07 \pm 0.01 \text{ Wm}^{-2}/\text{year}$). This is another counter-indication for the PMOD corrections and Fröhlich's choice of altered ERB to fit Lean's TSI model (Fröhlich and Lean 1998) rather than the original ACRIM1 results during this period. The PMOD/WSKF06 disagreement in this period and the agreement between the PMOD composite and Lean's proxy model (Fröhlich and Lean 1998) is yet another demonstration of the limitations of Lean's proxy model for characterizing TSI during this period.

7.3 Period 1985-1988: general agreement

From 1985 to 1988 good agreement is observed between the WSKF06, ACRIM1 and ERB results. No trend is found in their residual function given by Eq. 1. Good agreement is also seen between WSKF06 and PMOD and this is a direct result of PMOD's use of unaltered ACRIM1 results during this period. Overall, Figure 11 shows that from 1980 to 1988 there is better agreement between WSKF06 and ACRIM1 than between WSKF06 and PMOD.

7.4 Period 1988-1990: an upward shift of WSKF06

Figures 10 and 11 clearly show that WSKF06 diverges significantly from the results of ERB, ACRIM1 and the PMOD composite during 1988 to 1990. WSKF06 increases more rapidly than the TSI observations by about $0.3\text{--}0.5 \text{ W/m}^2$ (see Figure 11 for details). This indicates that WSKF06 does not reproduce TSI accurately during the ascending phase of solar cycle 22, as acknowledged by Wenzler et al. (2006). This period

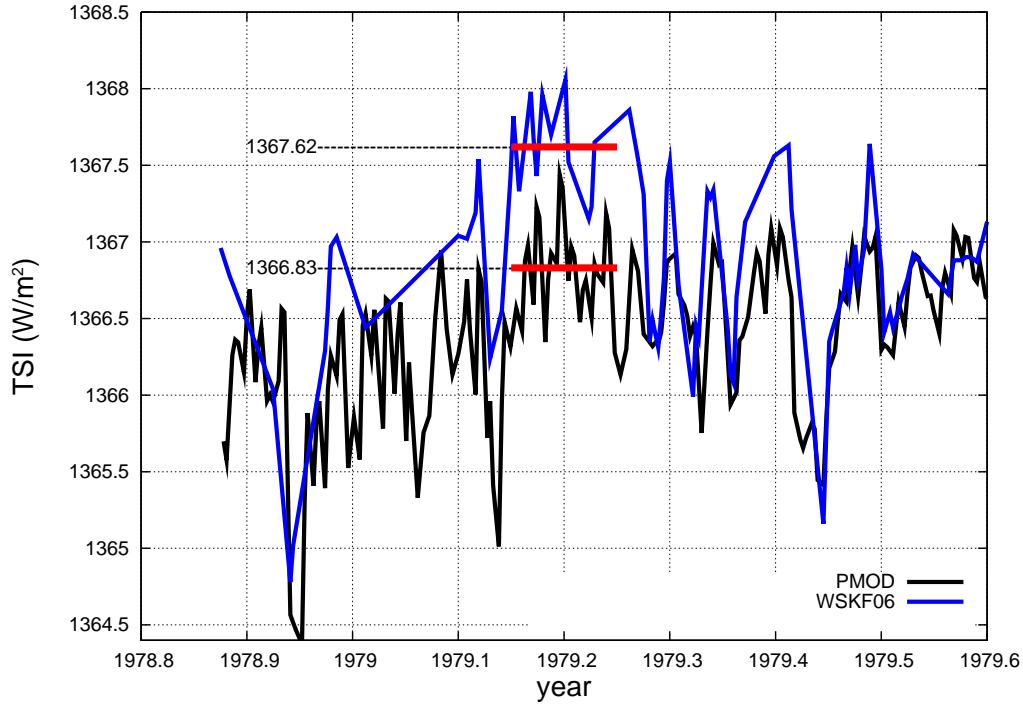


Fig. 12 WSKF06 standard TSI proxy model against the PMOD TSI composite. The large divergence between the two records during 1979.1-1979.3 corresponds to the peak in ERB results that was mostly removed by the PMOD science team to conform the TSI satellite records to the predictions of Lean's proxy model.

and the one before 1988 are mismatched by about 0.5 W/m^2 .

This is important because the Krivova et al. (2009) analysis disagreed with the earlier results of Scafetta and Willson (2009) in which a mixed ACRIM-KBS07 composite was constructed using KBS07 from 1988 to 1993 to bridge the ACRIM Gap and to merge ACRIM1 and ACRIM2. Krivova et al. (2009) used the same methodology of Scafetta and Willson (2009) but substituted the WSKF06 model for KBS07 and found a result different from ours. The mistake of Krivova et al. (2009) was their failure to recognize the drift of WSKF06 relative to ACRIM1 from 1988 to 1989 (see Figures 10 and 11), which clearly counter-indicates its use for merging ACRIM1 and ACRIM2. The 1988-1989 drift would cause an ACRIM-WSKF06 composite to artificially shift the 1980-1989 ACRIM1 data 0.5 W/m^2 upward relative to the 1992-2000 period. This artifact would reproduce the 1980-2000 PMOD pattern and obscure the 1980-2000 TSI upward trend that is common to both the ACRIM and ACRIM-KBS07 composites. Therefore, the criticism of Scafetta and Willson (2009) by Krivova et al. (2009) and their conclusions supporting the PMOD relative to the ACRIM composite is not correct.

7.5 Period 1990-1992.5: a Nimbus7/ERB upward drift?

Figures 10 and 11 show stationarity in the residual function (Eq. 1). Both the standard and optimum WSKF06 models are stable during the 1990-1992.5 ACRIM Gap period, and reproduce the trending of unaltered ERB results very well. Linear fits of the ERB-WSKF06 differences show no significant trends during this period for either the *standard* model ($0.003 \pm 0.03 \text{ Wm}^{-2}/\text{year}$) or the *optimized* model ($0.011 \pm 0.03 \text{ Wm}^{-2}/\text{year}$). By contrast the comparison of WSKF06 and PMOD during the same period reveals a very different result. The PMOD-WSKF06 difference linear fits have significant downward trending for both the standard and optimum WSKF06 models ($-0.16 \pm 0.03 \text{ Wm}^{-2}/\text{year}$ and $-0.146 \pm 0.03 \text{ Wm}^{-2}/\text{year}$ respectively). The PMOD/WSKF06 difference trends are comparable to the correction Fröhlich applied to ERB results during this period (see Figure 4). The discrepancy between PMOD and WSKF06 is a direct consequence of Fröhlich's downward adjustment of the ERB data.

The PMOD composite is based on a shift of ERB results totaling $\sim 0.86 \text{ W/m}^2$ during the ACRIM Gap, more than twice the $\sim 0.4 \text{ W/m}^2$ ERB shift derived from comparison with WSKF06 from 1990 to 1992.

Therefore, reconciliation of the PMOD composite to WSKF06 following the ACRIM Gap would require an upward adjustment of $\sim 0.46 \text{ W/m}^2$ that conforms the PMOD solar cycle 21–22 minima trend to that of the ACRIM composite.

7.6 Period 1990-1992.5 using the upgraded SATIRE model.

Ball et al. (2012) recently upgraded WSKF06. They show in their figures 7-10 that from 1990 to 1992.5 both the ACRIM TSI composite and the magnetogram-based SATIRE model trend upward during the ACRIM Gap while the PMOD trends downward. Figure 13 reproduces one of Ball’s figures where the upward trending of the unaltered ERB record, as used in ACRIM, is approximately reproduced by the SATIRE model, while PMOD slopes downward during the same period like ERBE.

7.7 Summary

In summary, the direct ERB-WSKF06 and PMOD-WSKF06 comparisons depicted in Figures 10, 11 and 13 during the ACRIM Gap support: (1) the correctness of the originally published ERB observations (within error bounds) that TSI increased during the ACRIM Gap; and (2) the hypothesis of Willson and Mordvinov (2003) that the ERB/ERBE difference during the ACRIM Gap is the result of ERBE degradation. Our results here directly contradict the PMOD hypothesis of an ERB sensitivity drift during October 1989 through mid-1992.

8 A close look at Lean’s TSI proxy model

The proxy model of Lean et al. (1995), based on linear regression of sunspot blocking and faculae brightening indexes against satellite TSI observations, was first used to guide and validate the PMOD hypotheses (Fröhlich and Lean 1998). As Figure 14 shows, Lean’s TSI proxy model presents a slight TSI decrease between the solar minima of 1986 and 1996, and a more evident TSI decrease during the ACRIM Gap from 1989 to 1992. These patterns were reproduced by PMOD by lowering the ERB results during the ACRIM Gap to essentially agree with the ERBE data. This gave an impression of mutual validation by Lean’s model and Fröhlich’s ‘ACRIM gap ERB glitch’ hypothesis. However, this is not the case as we will now discuss.

Limitations of the predictive capability of Lean’s updated model (Kopp and Lean 2011) can be demonstrated using the data of the last solar cycle. Lean’s

model predicts a 2008 TSI minimum higher than the minimum of 1996 by $\sim 0.1 \text{ W/m}^2$. However, this prediction is contradicted by both ACRIM and PMOD TSI composites that present the opposite trend with the 2008 minimum about $0.2\text{--}0.3 \text{ W/m}^2$ lower than the minimum in 1996 (see Figure 2). Other indices of solar magnetic activity (and TSI therefore), the open solar magnetic flux, the galactic cosmic ray (GCR) flux and additional solar indices all show solar activity higher in 1996 than in 2008 (Lockwood 2012). This demonstrates that on annual to decadal time scales Lean’s model is affected by a statistical uncertainty near $\pm 0.5 \text{ W/m}^2$. This is very nearly equal to the divergence of the ACRIM and PMOD TSI composites solar minima trends between 1986 and 1996 in determining (see Figure 2).

This discussion clearly indicates that use of Lean’s model as a guide to ‘re-evaluate’ published satellite observations is not able to add useful information to the understanding the TSI time series. Lean’s model cannot predict the decadal/multi-decadal trending of TSI with sufficiently accuracy to discriminate between the ACRIM and PMOD TSI composite trends. This applies in general and specifically to the validation of the PMOD composite by Lean’s model proposed for the period 1978-1992 (Fröhlich and Lean 1998).

9 Conclusion

We have conducted several independent evaluations of the accuracy of TSI satellite data and their composites. The ACRIM TSI composite relies solely on the continuity of the results of overlapping satellite experiments as understood and published by the flight experiment teams. The ACRIM composite has a direct and exclusively experimental justification (Willson and Mordvinov 2003). On the contrary, the PMOD TSI composite (Fröhlich and Lean 1998; Fröhlich 2004, 2006, 2012) is essentially a theoretical model originally designed to agree with Lean’s TSI proxy model (Fröhlich and Lean 1998). It relies on postulated but experimentally unverified drifts in the ERB record during the ACRIM Gap, and other alterations of the published ERB and ACRIM results, that are not recognized by their original experimental teams and have not been verified by the PMOD by original computations using ERB or ACRIM1 data.

Our findings support the reliability of the ACRIM composite as the most likely and precise representation of 35 years of TSI monitoring by satellite experiments. The only caveat is that the ERB record prior to 1980 may require some correction for degradation, but

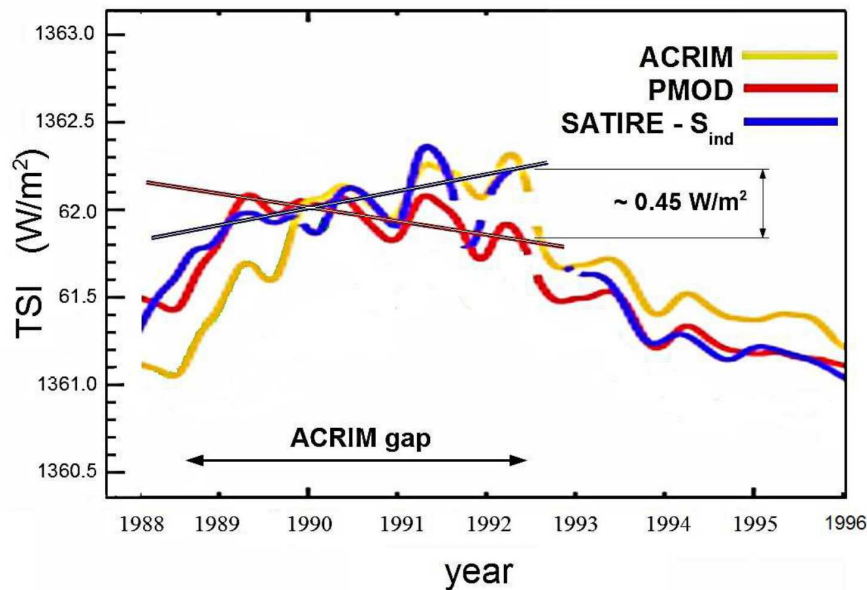


Fig. 13 Comparison of smoothed ACRIM and PMOD TSI composites and the magnetogram-based SATIRE-Sind TSI model during the ACRIM Gap (Ball et al. 2012). Note that from 1990 to 1992.5 the SATIRE prediction trends upward approximately like the ACRIM composite (slope = $0.1 \pm 0.03 \text{ Wm}^{-2}/\text{year}$) while the PMOD composite trends downward (slope = $-0.09 \pm 0.03 \text{ Wm}^{-2}/\text{year}$).

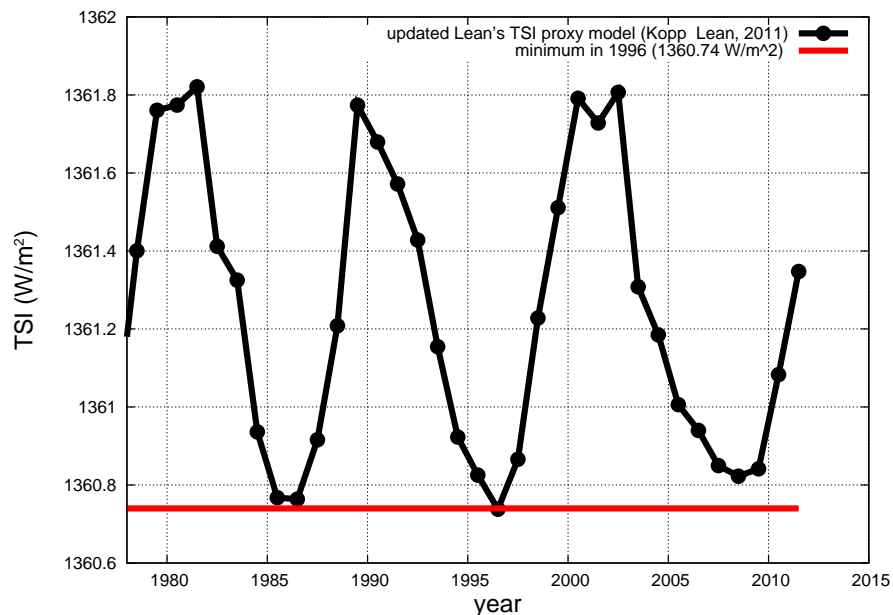


Fig. 14 Updated Lean TSI proxy model (Kopp and Lean 2011). Note that the TSI minimum in 2008 is about 0.1 W/m^2 higher than the minimum in 1996, which is contradicted by both ACRIM and PMOD (see Figure 2). Data from http://lasp.colorado.edu/sorce/tsi_{}data/TSI_{}TIM_{}Reconstruction.txt.

it would be much less than used in the PMOD composite.

We argued that the ACRIM composite most closely represents true TSI because the very corrections of the

published TSI data made by Fröhlich to construct the PMOD composite are not supported by a direct comparison between ERBE and ERB records in the proximity of September/October 1989.

Direct comparison of ERB and ERBE during 1989 showed that Fröhlich’s postulated Sep/29/1989 step function increase of 0.4 W/m^2 in ERB sensitivity, which coincided with a power down event, did not occur. The KBS07 proxy model does not support Fröhlich’s ERB ‘glitch’ either. A divergence between the two satellite records did occur in November 1989; but this is more than one month later and clearly not associated with the ERB end-of-September power down event.

We have demonstrated that the update of Lean’s TSI proxy model (Kopp and Lean 2011), used originally to validate PMOD’s lack of trending from 1980 to 2000 (Fröhlich and Lean 1998), has inadequate predictive capability to properly reconstruct the TSI decadal trending. Lean’s model predicted an upward trend between the TSI minima in 1996 and 2008 while both ACRIM and PMOD present a downward trend. This demonstrates that Lean’s proxy model cannot reconstruct TSI decadal trending with a precision smaller than $\pm 0.5 \text{ W/m}^2$ the same order as the difference between PMOD and ACRIM TSI composites. Thus, the use of Lean’s TSI proxy model is not useful as a guide to correct satellite measurements.

The WSKF06 TSI proxy models contradict the primary PMOD rationale by the following findings: (1) there was a TSI peak in late 1978 and early 1979 as recorded by ERB (although some early mission degradation of the instrument may have been uncompensated for); (2) the ACRIM1 published record is more stable than ERB during 1980-1984 and should be preferred for constructing a TSI composite during this period; (3) ERB did not experience either the end-September 1989 step function drift in sensitivity or the upward linear drift claimed by Fröhlich during 1990-1992.5. The latter result is also evident in the upgraded SATIRE model (Ball et al. 2012). Thus, if ERB requires some correction during the ACRIM Gap, our results suggest that Fröhlich overestimated those corrections by at least a factor of two due to the fact that at least one of the two hypotheses (the ERB glitch in Sep/29/1989 or the ERB drift from Oct/1989 to 1992) are not confirmed by our cross-analysis. The ERB-ERBE divergence during the ACRIM Gap most likely resulted from uncorrected degradation of ERBE in its first exposure to short wavelength fluxes driven by enhanced solar activity during the 1989-1993 solar maximum or other events. Consequently PMOD should be shifted upward by about 0.5 W/m^2 after 1992 which produces a 1980-2000 TSI upward trending similar to that observed in the ACRIM composite.

Our results demonstrated that the validity of TSI proxy models should not be overestimated since they frequently produce conflicting results and contradictory features. Although Solanki’s TSI proxy models

appear to reproduce the lack of a trend during solar cycles 21 - 22 in the PMOD TSI composite, they contradict one or more of the hypotheses advocated by PMOD to alter the originally published TSI used in constructing the PMOD TSI composite. Thus some of the arguments used to promote the PMOD composite (Fröhlich and Lean 1998; Wenzler et al. 2006; Krivova et al. 2007; Wenzler et al. 2009) are little more than speculations and coincidences. Moreover, Lean’s and Solanki’s TSI models differ significantly from the TSI model proposed by Hoyt and Schatten (1993) who constructed a TSI record since 1700 using five alternative solar irradiance proxy indexes — sunspot cycle amplitude, sunspot cycle length, solar equatorial rotation rate, fraction of penumbral spots, and the decay rate of the sun spot cycle.

Although Lean’s and Solanki’s models present no TSI trend during 1980-2000, as shown in the PMOD composite, there are other studies suggesting generally increasing TSI from 1970 to 2000. Shapiro et al. (2011) found a small increasing trend across the 1975, 1986 and 1996 solar minima followed by a decrease in the minimum of 2008. Also the cosmic ray flux index would suggest a solar activity increase from 1980 to 1996 (Scafetta 2013c, figure 20). The TSI pattern revealed in the ACRIM satellite composite is consistent with a quasi 60-year solar cycle modulation, which appears to be one of the major harmonic constituents of solar activity and should have theoretically peaked around 2000 (Ogurtsov et al. 2002; Scafetta 2012b; Scafetta and Willson 2013a; Scafetta 2013b). We conclude that solar activity may have presented a larger secular variability and specific geometrical patterns that are quite different from the Lean TSI model currently used to force the CMIP5 models.

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Appendix A: Hoyt’s statement about Nimbus7/ERB

In 2008 Scafetta asked Hoyt to comment the alterations of the ERB data implemented by Fröhlich to produce the PMOD composite. Hoyt returned by email the following statement where “N7” is for the Nimbus7/ERB TSI record prepared by Hoyt and collaborators:

September 16, 2008.

Dear Dr. Scafetta: Concerning the supposed increase in N7 sensitivity at the end of September 1989 and other matters as proposed by Fröhlich's PMOD TSI composite:

1. *There is no known physical change in the electrically calibrated N7 radiometer or its electronics that could have caused it to become more sensitive. At least neither Lee Kyle nor I could ever imagine how such a thing could happen and no one else has ever come up with a physical theory for the instrument that could cause it to become more sensitive.*

2. *The N7 radiometer was calibrated electrically every 12 days. The calibrations before and after the September shutdown gave no indication of any change in the sensitivity of the radiometer. Thus, when Bob Lee of the ERBS team originally claimed there was a change in N7 sensitivity, we examined the issue and concluded there was no internal evidence in the N7 records to warrant the correction that he was proposing. Since the result was a null one, no publication was thought necessary.*

3. *Thus, Fröhlich's PMOD TSI composite is not consistent with the internal data or physics of the N7 cavity radiometer.*

4. *The correction of the N7 TSI values for 1979-1980 proposed by Fröhlich is also puzzling. The raw data was run through the same algorithm for these early years and the subsequent years and there is no justification for Fröhlich's adjustment in my opinion.*

Sincerely, Douglas Hoyt

Appendix B: The importance of the TSI satellite debate for solar physics and climate change

The Sun is a variable star (Brekke 2012). However, the multi-decadal trending of solar activity is currently poorly modeled and numerous alternative proxy reconstructions have been proposed. Understanding the correct amplitude and dynamics of solar variability is important both for solar physics and climate change science.

The multi-decadal trending difference between the ACRIM (Willson and Mordvinov 2003) and PMOD TSI composites (Fröhlich and Lean 1998; Fröhlich 2006) shown in Figure 2 is important for understanding the multi-decadal variation of solar dynamics and therefore for discriminating among solar models used also to interpret climate changes. Because the ACRIM TSI composite shows an evident upward pattern from 1980 to 2000 while PMOD shows a slight downward trend during the same period, the former would suggest a larger

TSI low-frequency variability than the latter and different TSI multidecadal variation mechanisms. The origin of a slowly varying irradiance component may derive from changes in the solar faculae and/or in the background solar radiation from solar quiet regions. These mechanisms are currently poorly understood and modeled. However, if TSI increased from 1980 to 2000, total solar and heliospheric activity could have increased as well contributing significantly to the global warming observed from 1980 to 2000 (Scafetta and West 2005, 2007; Scafetta 2009, 2011, 2012a, 2013b,c).

The Coupled Model Intercomparison Project Phase 5 (CMIP5) used to study climate change (Scafetta 2013c) currently recommends the use of a solar forcing function deduced from the TSI proxy model originally proposed by Lean and collaborators (Wang et al. 2005; Kopp et al. 2007). Lean's recent models show a relatively small secular trend (about 1 W/m^2) from the Maunder minimum (1645-1715) to the present with a peak about 1960 and it is quasi stationary since. Alternative TSI proxy reconstructions have been proposed and some of them present much larger secular variability and different decadal patterns. Figure 15A depicts two of these sequences: Lean's TSI model and the TSI reconstruction proposed by Hoyt and Schatten (1993) rescaled at the ACRIM TSI level. Figure 15A also shows in blue the annual mean ACRIM TSI satellite composite since 1981 (Willson and Mordvinov 2003).

Hoyt and Schatten (1993, fig. 10) showed that their multi-proxy TSI model is highly correlated with an annual mean northern hemisphere temperature variation reconstruction since 1700. This correlation is confirmed (Figure 15B) by comparing a Hoyt+ACRIM TSI combination model against the Central England Temperature record since 1700 (Parker et al. 1992). The divergence observed during the last decades is likely due to an additional anthropogenic warming component which was far weaker in the past, as more clearly explained in the literature interpreting global climate change (e.g.: Scafetta and West 2005, 2007; Scafetta 2009, 2010, 2011, 2012a, 2013b,c). It has been demonstrated a good correlation between the same TSI proxy model and numerous climatic records for the 20th century including temperature records of the Arctic and of China, the sunshine duration record of Japan and the Equator-to-Pole (Arctic) temperature gradient record (Soon 2005; Soon et al. 2011; Soon and Legates 2013). Key features are a warming from 1910s to 1940s, a cooling from the 1940s to 1970s, a warming from the 1970s to 2000s and a steady-to-cooling temperature since ~2000, all of which correlate much better with the Hoyt+ACRIM TSI composite than with Lean's proxy model.

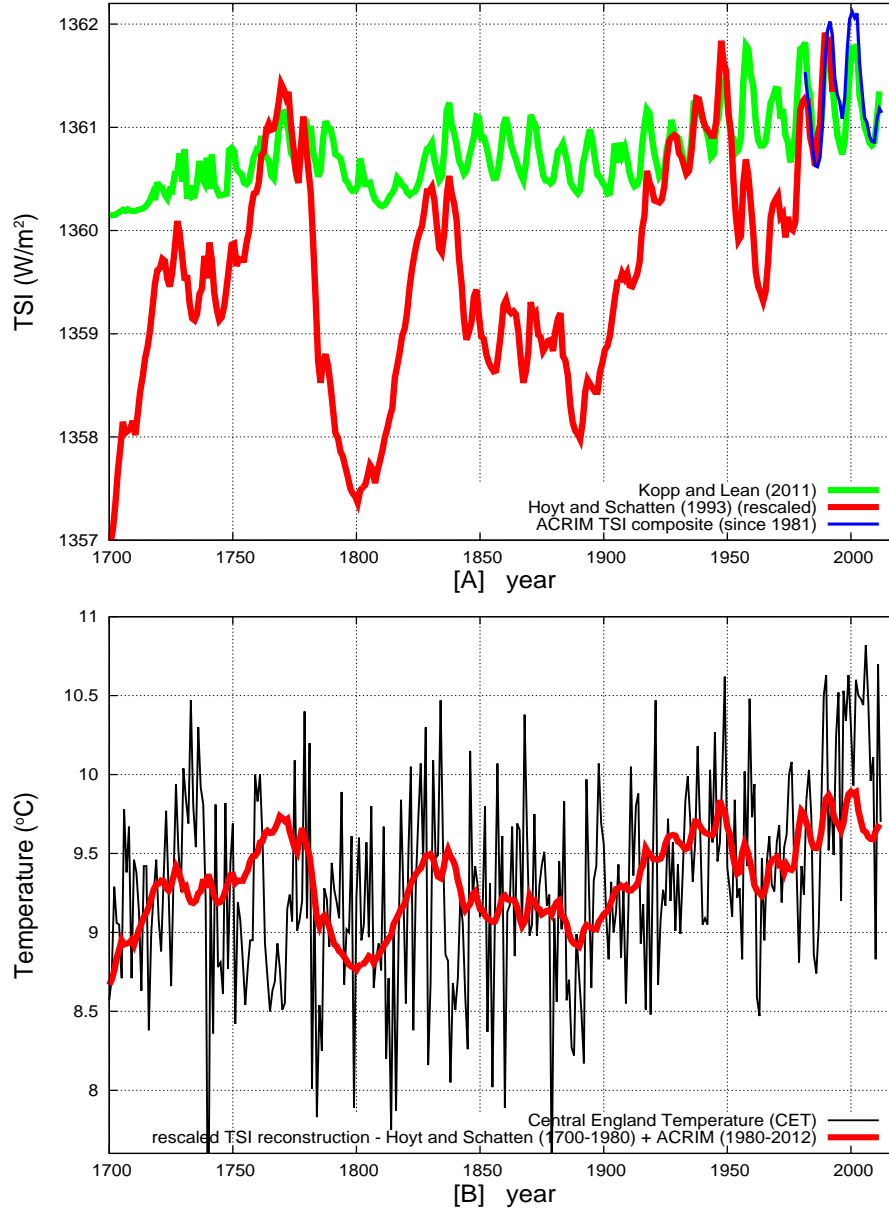


Fig. 15 [A] Total solar irradiance (TSI) reconstruction by Hoyt and Schatten (1993) (red) rescaled on the ACRIM record (Willson and Mordvinov 2003) (since 1981) (blue) vs. the updated Lean model (Wang et al. 2005; Kopp et al. 2007) (green). [B] Comparison between the Central England Temperature (CET) record (black) Parker et al. (1992) and the TSI model by Hoyt and Schatten plus the ACRIM TSI record. Good correlation is observed at least since 1772. (Note CET is less certain before 1772). The Hoyt and Schatten (1993) reconstruction has been made by rescaling it on the ACRIM record from 1980 to 1992 using the formula $HS93 * 1361.267 / 1371.844$, where 1371.844 is the 1981-1992 average of Hoyt and Schatten (1993)'s proxy reconstruction and 1361.267 is the 1981-1992 average of the ACRIM TSI composite. The value in 1980 in [B] was estimated as the average between the ACRIM mean and the rescaled Hoyt and Schatten (1993) reconstruction.

Recently, Liu et al. (2013, see also the supplementary information) used the ECHO-G model and showed that to reproduce the $\sim 0.7^{\circ}\text{C}$ global cooling observed from the Medieval Warm Period (MWP: 900-

1300) to the Little Ice Age (LIA: 1400-1800) according to recent paleoclimatic temperature reconstructions (e.g.: Ljungqvist 2010; Mann et al. 2008; Moberg et al. 2005), a TSI model with a secular variability ~ 3.5

times larger than that shown by Lean's TSI model would be required.

The IPCC (2007, section 6.6.3.4 and its figure 6.14) reports that to obtain a cooling of about 0.7°C from the MWP to the LIA Maunder Minimum a corresponding TSI downward trend of -0.25% is required. Lean's TSI model shows a trend of only -0.08% over this period (Wang et al. 2005). The same climate models rescaled using Lean's TSI model predict a MWP-to-LIA Maunder Minimum cooling of only 0.25°C that is compatible only with the controversial hockey stick temperature reconstruction of Mann et al. (1999). It should be noted that the updated proxy temperature reconstructions by Mann et al. (2008) show a significantly warmer MWP than the Mann's 1999 temperature reconstruction used by the IPCC in 2001.

Thus, recent paleoclimatic temperature reconstructions imply that the natural climate variability varied significantly more than predicted by the CMIP5 general circulation models, which use Lean's low-variability TSI model (e.g.: Scafetta 2013a,b,c). The most likely explanation is that solar variations are a more significant contributor to climate change than currently understood (see also: Liu et al. 2013; Scafetta 2013a). A stronger solar effect on the climate would also imply a significantly larger solar contribution to the 20th century global warming, as demonstrated in some works (Scafetta 2009, 2013a,b,c). Indeed, despite the IPCC (2007) claims the sun has an almost negligible effect on climate, numerous authors found significant correlations between specific solar models and temperature records suggesting a strong climate sensitivity to solar variations (e.g.: Bond et al. 2001; Hoyt and Schatten 1993; Loehle and Scafetta 2011; Mazzarella and Scafetta 2012; Ogurtsov et al. 2002; Scafetta 2009, 2010, 2012b, 2013b; Schulz and Paul 2002; Soon 2005; Soon and Legates 2013; Steinhilber et al. 2012; Svensmark 2007; Thejll and Lassen 2000).

Recently, Shapiro et al. (2011) and Judge et al. (2012) also proposed TSI models based a comparison between solar irradiance reconstructions and sun-like-stellar data that show a TSI secular variability at least 3-to-6 times greater than Lean's TSI proxy, similar to those proposed by Hoyt and Schatten (1993). The Shapiro model also predicts a small TSI increase between the solar minima of 1986 and 1996, that is more consistent with the ACRIM 1980-2000 upward TSI pattern and contradicts PMOD. This pattern derives from the fact that the cosmic ray flux record, which is inversely proportional to solar magnetic activity, presents a slight decrease from about 1970 to 2000 (Scafetta 2013c, figure 20).

It was recently speculated that long term changes in the solar interior due to planetary gravitational

perturbations may produce gradual multi-decadal and secular irradiance changes (e.g.: Abreu et al. 2012; Charbonneau 2013; Scafetta 2012b,c; Scafetta and Willson 2013a). The planetary models proposed by Scafetta (2012b) and Scafetta and Willson (2013a) shows a quasi 60-year modulation of solar activity since 1850 with peaks in the 1880s, 1940s and 2000s. Thus, it shows good agreement with the ACRIM composite's upward trending from about 1980 to 2000.

In conclusion, despite recent scientific climate change literature (e.g.: IPCC 2007) has favored the PMOD interpretation of the TSI experimental records we have provided experimental and theoretical reasons for our belief that the ACRIM TSI composite is a most likely interpretation of the current satellite TSI database. The dynamical pattern revealed by the ACRIM TSI composite appears to better agree with a number of new evidences that are emerging and, therefore, solving the TSI satellite controversies could be quite important for better understanding solar physics and climate change alike.

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